JOURNAL OF APPLIED PHYSICS

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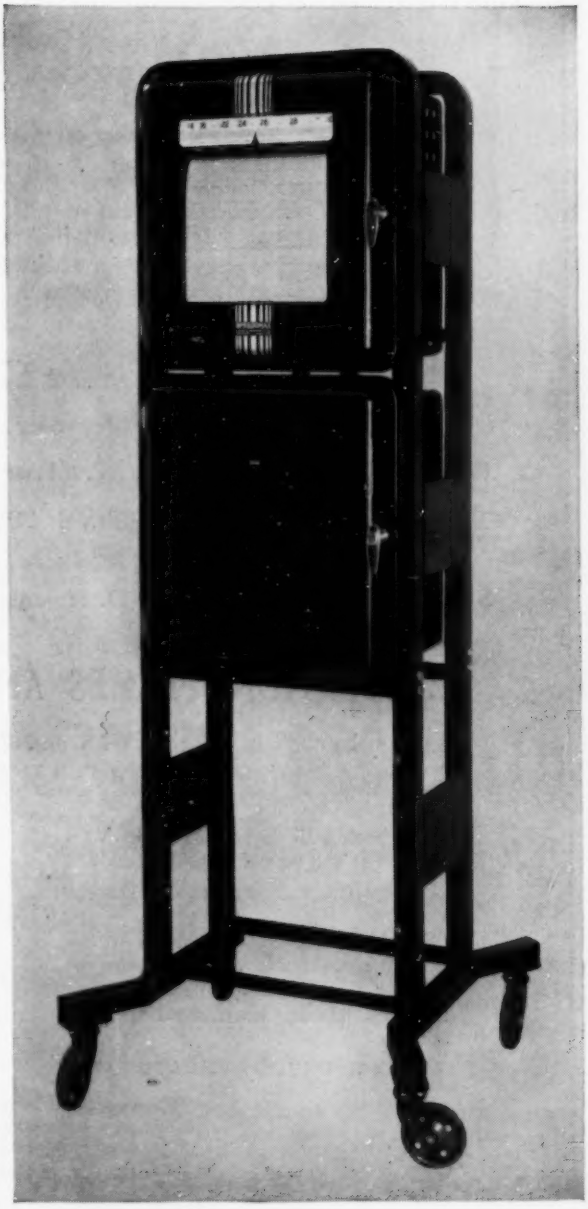

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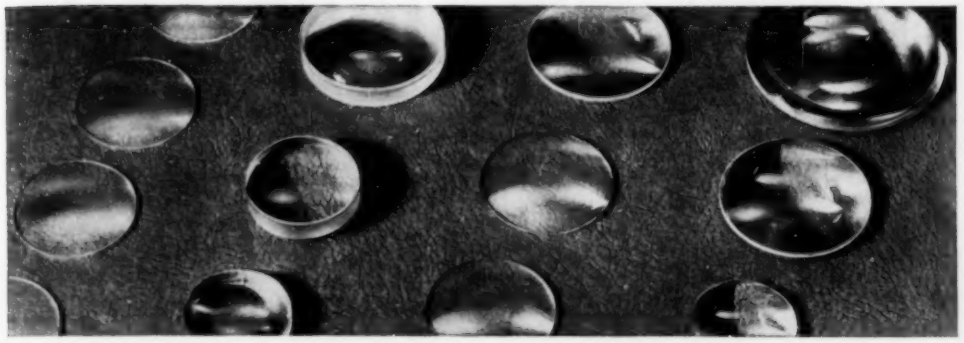

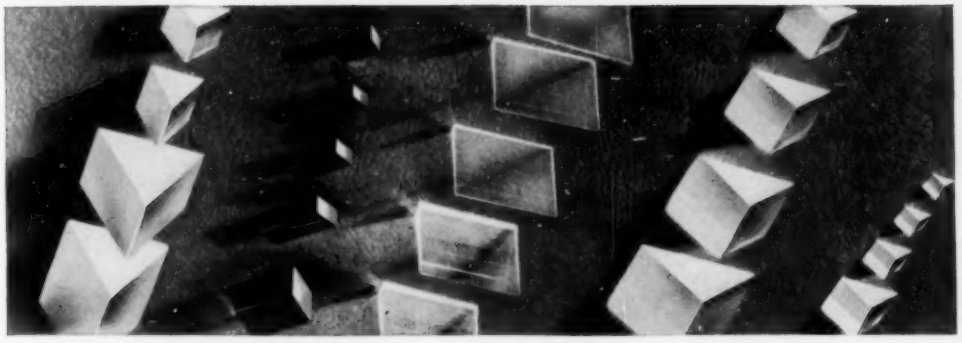

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Television, a Task Well Begun

A PAINTING by an old master, a Brahm's symphony or a fine piece of machinery gives one a thrill that sends a tingle down the spine. Somewhat the same feeling comes over one when he reads of the progress that has been made in television. The hand of the expert is readily apparent from the attention which has been paid to the most minute details. One marvels at the ingenuity which has been needed to overcome almost superhuman difficulties. These difficulties have disappeared one by one until now we have something worth talking and writing about.

Thus we are brought to the subject of the present issue of the *Journal of Applied Physics*. In it we are told of the most recent practice in commercial television. We are told how the light from an outdoor scene is "picked up" and transformed into a series of electrical impulses. These impulses come so rapidly that the problems which they introduce when one attempts to transmit them from point to point form a story by themselves. Next comes a story of the receiving of these impulses and the re-formation of the scene in our own homes. The scene which we see is really a fluorescence caused by a focused beam of electrons. Papers on electron optics and fluorescence are therefore included to complete the technical side of television.

There is however another side to this discussion. The scientist has often been called the modern frontiersman. Television represents one of the most recent frontiers of science. Just as with the extending of geographical frontiers, new problems and new responsibilities have arisen. Television has a great potentiality for good and for bad. Some of the probable influences are also discussed in this issue. Let us hope that as much wisdom will be spent in making use of television as has been spent in bringing it to its present level of technical perfection.

Acknowledgment

The present issue would have been impossible without the generous cooperation of our Associate Editor, Dr. V. K. Zworykin of the RCA Manufacturing Company, Incorporated. The Editor wishes to express his sincere appreciation to Dr. Zworykin.

For August

Sound Measurements in Industry, by ERNEST J. ABBOTT

Applied Physics in the Bureau of Home Economics, by MARGARET B. HAYS

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Also contributed original research.

Probable Influences of Television on Society

BY DAVID SARNOFF

President, Radio Corporation of America, New York, New York

I.

TO DISCUSS the effect which the general introduction of a new scientific development may have upon society is like attempting to predict, at his college commencement, the future career of a young man whom one has known from childhood. In the radio industry we have known television in this way, in a sense, for many years. We have watched its progress through the laboratory, and have encouraged it with financial and moral support while it struggled with the creation of sound fundamental principles upon which the future matured art must be based. We observed the coming and going of numerous irrational fancies, in methods and devices, during its adolescence.

Finally television is becoming adult, integrated in its technical standards and practices, with a cathode-ray system which has been uniformly adopted by the engineers of the radio industry. Yet, its maturity thus far has been attained only within the protecting confines of the homes and workshops of its scientific guardians. This Spring it graduated from this protective environment, and was thrust out to make its way in the world. What will it offer to mankind, and what response will mankind make to it?

Ever since the beginning of time man has sought to extend the power of his senses and to enlarge his capacity to perceive and respond to the world around him. Until a few centuries ago these instinctive strivings could utilize only the limited powers of the normal human senses and bodily capacities, unaided by scientific devices; so that adventurers wandered over the face of the earth on arduous journeys, and sailed the seas in lonely ships, to learn more of the nature of the world and to come into contact with the inhabitants of far-off places.

Writing and printing first enabled men to extend the power of their voices in order to communicate thoughts. With this extension of the powers of speech and hearing, the less gifted and less adventurous spirits could begin to apprehend the experiences and philosophy of those who were more fortunate in their mental or physical capacities, and thus satisfy vicariously their own instinctive desires for wider participation in the world's affairs.

Then, only a few hundred years ago—a tiny fraction of time compared to the ages that went before—man stumbled upon the scientific method. Inventive minds began to use basic scientific laws and principles for constructing devices which would fulfill many ancient human yearnings. Machines were made which multiplied many-fold the capabilities of human hands and muscles; optical instruments began to enhance the power of vision; railroads, steamships and automobiles increased the powers of locomotion and gave people the means of satisfying more readily the age-old desire for visiting other lands and places; communication devices brought distant friends and relatives close together.

One by one the shackles that chained man to the limited sphere of his own mind and his immediate neighborhood have been struck from him. Today he can move his body about rapidly, easily and at will; he can enlarge the powers of his hands and arms thousands of times; he can extend his voice by radio to other men throughout the world, and hear them in return. Now the last shackle is about to be broken; through television his eyesight promises to become all-embracing and world-wide. And not only is he given the power to see at great distances those things which may be evident within the limited spectrum of the visible rays of light, but also those which heretofore have been invisible because they could only be perceived through the use of waves outside the visible region.

II.

With the advent of television a new force is being given to the world. Who can tell what the

power to extend vision will mean ultimately in the stream of human life? Could anyone have foreseen the vast social effects of electricity inherent in the voltaic cells of the early physicists or in the experiments of Faraday? Could we have foreseen that technological unemployment would be seriously regarded by some as a social consequence of the evolution of tools from the primitive axes and knives of our ancestors to the complex labor-saving devices of the present day? The most audacious imagination could not have envisioned the vastly ramified applications of electronic devices which have grown out of Edison's first observation of electron emission from the heated filament of a lamp.

Thus, it would require courage indeed to attempt to estimate the ultimate effects of television and all the scientific or social consequences that may flow from its introduction. We know only that inventions which gave us new powers have had far-reaching results in the history of the human race. Professor W. F. Ogburn has made a special study of the social effects of inventions, and in one of his papers he has pointed out some striking instances. For example, it is said that the use of gunpowder was a powerful factor in breaking down the system of life built around the feudal lord and his castle; the use of steam in connection with machinery greatly changed family life by taking industrial production out of the home and into the factory; important inventions of the past fifty years such as the telephone, the automobile, the airplane, the motion picture and radio are producing far-reaching effects on the family, government, education, industrial production, the habits and beliefs of people, and the economic well-being of nations. The social effects of inventions such as the airplane, radio and rayon have only just begun, comparatively speaking, and the effects of the telephone, the automobile and the motion picture are far from being completed.

Furthermore, Ogburn shows that an invention has primary and derivative effects. He says:

"The primary effect of the 'power inventions' namely steam, gasoline engines and electric motors has been upon the economic or industrial organization of the family; women went to work outside the home, children were employed in factories, and the father ceased to be much of an employer or manager of household labor. There followed a shift of authority from father and home to industry and state. In cities homes became limited as to space, and more time was spent outside by the members of the family. In a similar way, inventions impinged upon government, because of the growth of large corporations for manufacturing and for providing services which were made possible through power inventions. The regulatory functions of government increased, and taxation methods were modified. Many more government activities were assumed or engaged in through the force of the circumstances created by the changed economic organization. Finally, another derivative effect occurred in connection with modifications of social views and philosophies. Attitudes toward a philosophy of laissez faire are undergoing changes as more and more governmental services are demanded. Attitudes toward recreation and leisure time change, with city conditions and repetitive labor in factories."

We have some basis for predicting the probable *primary* social effects of television by regarding it as an extension of the present system of aural broadcasting. Indeed, some of the sociologists who have given consideration to this subject believe that a new series of effects more important than those of sound broadcasting are not likely to occur. S. C. Gilfillan says in this connection:* .

"In ordinary life the eye is used more in perception than the ear. It has been suggested, therefore, that visual broadcasting when perfected will have even more important effects than aural broadcasting. Such an idea must be accepted with caution. From the social standpoint, the most significant development took place when radio made it possible to send news, music and propaganda through the air into the home. Six years ago the authors of the chapter of 'Invention' in *Recent Social Trends* were able to list 150 social effects of radio in its aural form. It does not seem likely that television will introduce a new list of social effects which is longer or more important. Addition of sound to pictures doubt-

*S. C. Gilfillan, "Social Effects of Inventions," in *Technological Trends and National Policy*. Report of the National Resources Committee, Washington (1937).

less produced relatively few new social effects of the cinema. Addition of pictures to sound should be more important in the case of radio, because of the greater use of the sense of vision than of the sense of hearing. Yet it is likely that the main impact of television will be to intensify the social effects which broadcasting already is producing."

While on the whole, this seems to be a sound line of reasoning, nevertheless the degree of intensification of present-day social and psychological effects of radio may be such as to produce a new series of changes in human lives and habits. Television will finally bring to people in their homes, for the first time in history, a complete means of instantaneous participation in the sights and sounds of the entire outer world. It will be more realistic than a motion picture, because it will project the present instead of the past. Aural radio already has demonstrated the greatly heightened psychological significance, to the listener, of feeling that he is present at the radio performance, as a member of an audience listening to living performers. The sensation that one is participating in an event actually taking place at the precise moment of hearing it is quite different and much more intense than the sensation one has in witnessing a sound picture or hearing a record of the same event, later on. With the advent of television, the combined emotional results of both seeing and hearing an event or a performance at the instant of its occurrence become new forces to be reckoned with, and they will be much greater forces than those aroused by audition only. The emotional appeal of pictures to the mass of people is everywhere apparent. We have only to regard the success of motion pictures, tabloid newspapers and modern picture magazines, to be convinced of this.

III.

Let us consider next what sort of program material television may present to its audience. Radio programs today cover almost every conceivable type of material that may be of value as entertainment, instruction and news. But while the scope of television programs will be equally broad, it is clear that the relative emphasis on the various types of subject matter can be changed to advantage. In aural radio we tend to emphasize program material that may be enjoyed without the use of vision; hence music forms a major part of aural radio programs. In television it will be natural to emphasize types of program material where the addition of visibility will enhance the emotional effect—such as drama, news, or sporting events.

Radio already has made significant contributions to novel dramatic forms and materials. Experimentation is constantly going on, under the daily pressure of providing ever-changing programs. Famous dramatists, actors and producers are turning in increasing numbers to radio as a new and important medium, and the intellectual standard of much radio drama is in the best tradition of the legitimate theatre. With the advent of television, a new impetus will be given to this form of art, and we may expect it gradually to take the place of some other types of programs which now occupy a large part of radio time.

While some television dramas may be recorded on film, for convenience or for network distribution, it is not certain that the standards, methods or artistic ideas of the present-day motion picture industry will control the material presented. Radio has always been an independent force, and has broken new ground in what it has done. A first-class radio program is like no theatrical or motion picture presentation that ever was. It is a new thing in the world. Similarly, it is quite likely that television drama will be a new development, using the best of the theatre and motion pictures, and building a new art-form based upon these.

It is probable that television drama of high caliber and produced by first-rate artists, will materially raise the level of dramatic taste of the American nation, just as aural broadcasting has raised the general level of musical appreciation.

Advertisers who sponsor radio programs will be given new possibilities of appeal through the medium of television. We need not fear, however, that this will mean an increase in the amount of "sales talk." In fact, it is probable that pictures or demonstrations of the product with the briefest possible messages will take the place of the more extensive announcements which are necessitated by the limitations of aural radio.

Political addresses will be more effective when the candidate is both seen and heard, and is able to supplement his address with charts or pictures. Showmanship in presenting a political appeal will be more effective than mere skill in talking, or the possession of a good radio voice; while good appearance may become of increasing importance, with the audience observing the candidate in close-up views.

An outstanding contribution of television will be its ability to bring news and sporting events to the listener while they are occurring. The widespread public participation in events such as those which occurred during the European war crisis in the summer of 1938, and the intensity of the mass emotions aroused thereby, have given us a glimpse of the possibilities of this phase of radio. It may readily be imagined what will be the results when television adds to the effect of reality by projecting the vision as well as the hearing of the audience to the scene of action.

Some social scientists have pointed out the greater possibilities of propaganda when presented by television. The great mass of the human race is not critical, and temporarily, at least, may be swayed by appeals to the emotions rather than to reason. In European countries which have succumbed to dictatorships extraordinary changes have been brought about in a very short time, with the aid of radio propaganda, in the expressed beliefs and actions of vast populations. These have been led to accept whole ideologies contrary to their former beliefs, because of skillfully presented ideas which have been spread to every home in the land with the speed of light and with a minimum of effort. The advent of television makes it even more important than heretofore to preserve for radio broadcasting in our country the precious right to freedom of discussion, and to guard against its exploitation for transmitting propaganda intended to arouse destructive class struggles, racial animosities or religious hatreds.

Educational institutions are gradually adopting mechanical inventions as aids to teaching, and radio receivers as well as phonographs are becoming increasingly familiar sights in schoolrooms. Because of these, the children of today have heard immeasurably more good music, and are more keenly conscious of world history in the making, than those of the previous generation. The possibilities of sound motion pictures for vitalizing and dramatizing scientific subjects, geography and history have been demonstrated; but schools are slow to make use of these because of the expense of the films, and the lack of organization among the hundreds of thousands of school administrations where cooperation is necessary in such a large-scale undertaking. With television we may find the educational uses of radio increasing; for while children may be bored and restless when merely listening to a speaker without seeing him, living pictures will capture and hold their interest.

IV.

There is another aspect of television which is important, and this is the nature and effects of its by-products. New instrumentalities have been developed, specifically for the purpose of transmitting visual intelligence by radio. These include iconoscopes, or devices for converting a light image into electric currents, amplifiers of wide frequency range, high powered, ultra-short wave transmitters and kinescopes which reproduce the original image by converting electric currents into light. All these devices are beginning to find applications in fields remote from television, and, as familiarity with them grows, their fields of application no doubt will be extended.

The whole subject of electron optics, or the control of electron beams by electric and magnetic fields, has received great attention because of its importance in television devices. This has led to a whole new range of possibilities in optical devices. Applications of this to astronomy, and in other fields where weak or distant sources of radiation must be dealt with, are future possibilities.

Some of the fields in which these television devices may bring about important advances are in marine or aerial navigation, by permitting vision at night or in fogs through the use of infra-red rays; in metallurgical, chemical, physical and biological research; in manufacturing processes as substitutes for human vision or for control purposes; in national defense; for advertising or display use in department stores, in showing goods exhibited at a central point

throughout the store or in show-windows; for personal or business communication in transmitting visual intelligence as we now transmit the voice by telephone; in printing and copying devices; in new photographic or motion picture devices where "light amplification" may be used to advantage; and in any other fields where an automatic, never-failing substitute for the human eye may be useful.

V.

I have suggested some of the more immediate possibilities in the effects upon society of the advent of television. What of the more distant future, or *derivative* effects?

It seems to be the general opinion of authorities on population trends that life in the United States several decades from now will differ in important respects from that of the present time. The chief events which are anticipated are a continued increase in leisure time, an increase in the average age of the population, and a greater geographic decentralization or distribution of industry. The application of television devices will affect and be affected by these occurrences.

The average length of the full-time week for industrial workers has decreased from nearly 60 hours in 1890 to less than 40 hours at the present time. Improvements in manufacturing methods have had the effect partly of raising wages and partly of decreasing the working week. There is every reason to expect a continuance of these processes, considered on a long-time basis. The combined ingenuity of the social and physical scientist, encouraged by a sympathetic government, should in time produce the much desired results of more pay, shorter hours of labor and longer hours of leisure.

At the same time, if the birth rate continues its present declining tendencies, the distribution of population in accordance with age will alter materially. Population experts have estimated that whereas in the 1930 census only 23 percent of the population was over 45 years of age, by 1980 we will have 38 percent of the population in this age group. The whole tendency will be towards a predominantly middle-aged and elderly population.

A decline in the population of large cities is expected by the National Resources Board to set in some time between 1945 and 1960, with people moving into "satellite" areas within the metropolitan districts. We have already observed how the introduction of the automobile spurred the development of suburbs of large cities. Now, with steadily cheaper cars, increased and improved highways, it is anticipated—and the tendency is already clearly evident—that rural communities within perhaps fifty miles of the cities will increase in population and develop in scope.

All this provides a picture of a population which may increasingly center its interests once more in the home; a population with ample leisure time, of predominantly mature years, and widespread distribution, in individual small houses which they will be able to afford because of the development of low-cost home construction and increased income per family. With such a setting, radio-television will be a vital element in the lives of these people. It may become their principal source of entertainment, education and news. It will link together in mind and spirit these vast numbers of individual homes, as the high speed automobile roads and airways will link them together physically.

We may also anticipate a rising standard of culture, with universal education of both adults and children. New York State is now considering the extension of the present high school courses to six years; if this plan is widely adopted, we will soon have the equivalent of junior college training established as the minimum standard for graduates of our public school system. In the distant future of which we speak, it may be assumed that most persons will have at least an education of this level. What this may mean in terms of the type of material to be broadcast, and its place in the cultural life of the community, is stimulating to the imagination.

We have seen how much the general level of musical taste in this country has already been raised by the widespread radio broadcasting of good music. People to whom such matters as grand opera and symphonic music were unknown fifteen years ago are becoming increasingly familiar with them. With television, a similar widening cultural development in appreciation of the best in drama, the dance, painting and

sculpture may be expected. Through television, coupled with the universal increase in schooling, Americans may attain the highest general cultural level of any people in the history of the world.

What of the effects upon existing institutions, such as motion pictures, the theatre, schools and churches?

The motion picture industry may become an important source of supply of recorded programs to television broadcasters, where such recordings may serve the purposes of program material more conveniently than direct transmission of living actors. There are other possibilities too for cooperation between the motion picture industry and television. Each should be able to stimulate the other and this should result in an enlarged service to the public.

With a rising cultural level, we may expect also an increase in the number of creative artists working with the materials of the theatre. Such artists will be used not only by the television broadcasting systems; they will find additional outlets for their creative energies. Through these new developments we may see a rebirth of local community theatres for the production of legitimate drama, musical performances, dances, and the like.

The school systems will probably make increasing use of television as part of the educational program; for with this medium it will become possible for the best teachers in the land to give carefully prepared and illustrated lectures to millions of children simultaneously.

Church broadcasting will rise to new spiritual levels, for with television the listeners can participate most intimately in the services of the greatest cathedrals; they will not only hear the ministers and the music, but see the preacher face to face as he delivers his sermon, witness the responsiveness of the audience, and observe directly the solemn ceremonies at the altar.

Thus, the ultimate contribution of television will be its service towards unification of the life of the nation, and at the same time the greater development of the life of the individual. We who have labored in the creation of this promising new instrumentality are proud to launch it upon its way, and hope that through its proper use America will rise to new heights as a nation of free people and high ideals.

Survey of Television Pick-Up Devices

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IN A television system the "pick-up device" serves to translate the information contained in the light energy, arriving from a viewed object, into a particular wave form of an electric current. It occupies a position corresponding to that of a microphone in a sound reproduction system. The task which the pick-up device must accomplish is much more difficult than that of the microphone, since two spatial dimensions are involved in the television problem, in addition to time.

Two methods of handling the space problem have been suggested historically. The first is to use a group of light sensitive devices at the transmitting point, arranged in a plane perpendicular to the direction of viewing and individually connected to a group of similarly placed reproducing devices at the receiving point. Each reproducing device should maintain a brilliance proportional to that of the light arriving at the corresponding position at the transmitting point. The detail which can be shown in a system of this type depends on the cross-sectional area occupied by the separate pick-ups and receivers, since each pick-up is affected by the *total* flux of light incident on it, and each reproducer must produce an even brilliance over its area. While such a multichannel system works satisfactorily for pictures with little detail, the amount of equipment required and the physical size of available pick-ups and reproducers forbid its use where high definition is required.

The other possibility and the one universally used in high definition television systems is that each portion of the picture be viewed in succession, or *scanned*, and that the retentivity of the eye be relied upon to reproduce the picture as a whole. This requires that the whole picture be scanned in 1/24 of a second or less. When 60-cycle power is used it is desirable that an integral submultiple of the power frequency be chosen as the rate of repetition of the whole picture (called the *frame frequency*), so that the effect of any unfiltered ripple in the power supply will appear in the same place in successive pictures and not appear to drift across the field of view. In present systems the entire picture is repeated 30 times a second. While such a system requires only one electrical channel, since only one bit of information is being sent at a time, it imposes much more rigorous requirements on all the circuits and devices concerned. Each picture element contributes to the picture for only a small fraction of 1/30 of a second, depending upon the number of elements into which the picture is divided. In a modern high definition system the picture is divided into 441 horizontal lines. Since the width of the picture is usually about 4/3 of the height (aspect ratio 4 : 3) and the scanning aperture is symmetrical, there will be effectively 259,308 ($441\times441\times4/3$) separate picture elements. Thus each picture element will be allotted less than one seven-millionth of a second to transmit its information to the receiving point. This requires either a high level of illumination or a very sensitive pick-up device, or both, since the electric current flowing is a function of the total *amount* of light reaching the photoelectric device at any instant.

The scanning at the transmitting and receiving points must be in synchronism, so that each element of the viewed object will be seen in its proper relative position at the receiver.

Pick-up devices in use today are divided into two general classes: mechanical scanners and electronic devices. A mechanical scanner in general comprises either a revolving Nipkow disk with small apertures in it, so that at any instant only one small portion of the object can project light onto the light sensitive device, or some rotating device which can sweep a spot of very high intensity light over the viewed object, so that only that light from the highly illuminated portion of the object affects the light sensitive device. While mechanical scanning is still used

in some European systems it is not now used in this country to any considerable extent.

Current American practice employs electronic pick-up tubes exclusively. Two such tubes, the iconoscope[1] and the image dissector,[2] have been brought to such a state of development that practical high definition television systems can be built around them. Attention in this article will be concentrated exclusively on them.

Both of these tubes are small in size and light in weight so that they are readily adaptable for use in portable set-ups. They are both able to handle outdoor scenes under normal daylight conditions, including moderately cloudy days, or to work under illumination conditions similar to those in motion picture studies. They are also able to operate with motion picture film as a source of program. All this with the present accepted standard of 30 frames per second,[3] 441 lines, and interlaced scanning. A typical television camera is shown in Fig. 1.

The Image Dissector

The image dissector operates by converting the optical image into an "electron image," and then scanning the electron image. An electron image consists of a space flow of electrons such that the density of electrons at any point in a cross section of the flow is proportional to the light intensity at the corresponding point of a similar cross section of the optical image reaching the dissector tube.

The essential parts of the tube are: a photoemissive cathode, on which the light from the picture is focused; an accelerating anode to draw the emitted photoelectrons away from the cathode; a magnetic focusing field, to insure that the electrons from any point on the cathode surface arrive at a corresponding point in the plane of the scanning aperture; a small scanning aperture to segregate the electrons from an individual picture element; an electron multiplier to intensify the tiny currents collected through the scanning aperture; and a pair of deflecting coils, creating two magnetic fields, perpendicular to one another and to the direction of electron travel, which sweep the electron image across the scanning aperture so that successive picture elements can contribute their quotas of electrons. The cathode, anode, scanning aperture, and electron multiplier are mounted in an evacuated glass cylinder about 13 inches long and 4 inches in diameter. The end of the cylinder away from the photoemissive surface is an optically clear window through which the optical image is focused on the cathode. The electron focusing and deflecting coils are mounted just outside the evacuated tube. The arrangement of the various elements is shown in Fig. 2 (an old type multiplier was used in this tube) and a photograph of the tube without deflecting and focusing coils is shown in Fig. 3.

FIG. 1. Portable television camera. (Courtesy of RCA Mfg. Co.)

Theory of Operation

Light falling on the photoemissive cathode causes electrons to be emitted from each small area; the number of such electrons is a function of the intensity of the light incident on the area. These photoelectrons are accelerated from the cathode toward the anode, which is located at

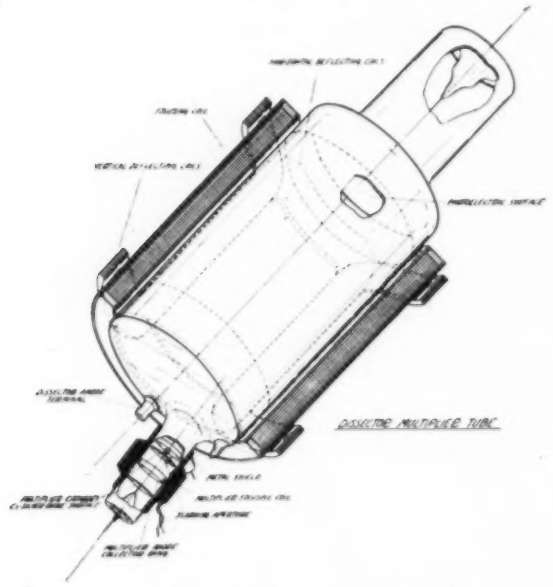

Fig. 2. Arrangement of elements in image dissector. (Courtesy of Farnsworth Television, Inc.)

the same end of the tube as the scanning aperture; they are focused by the combined action of the electrostatic field of the anode and the axial magnetic field so as to form an electron image in the plane of the scanning aperture. This electron image is caused to deflect as a whole, both horizontally and vertically, by the application of transverse magnetic fields.

For the simplest type of scanning the horizontal field causing vertical deflection would be varied in strength in a sawtooth fashion so as to cause complete deflection of the image in 1/30 of a second. The vertical field would be varied (also in a sawtooth fashion) so as to cause complete horizontal displacement in the length of time allotted to one line (approximately 7×10^{-5} second). This would mean that a particular portion of the picture at the receiving point would be illuminated only once every thirtieth of a second. A field which is illuminated at that rate appears to the eye to flicker. This is particularly true if the light is viewed near the edge of the eye's field of vision. To avoid this impression of flicker alternate lines are scanned, so that the whole field of the picture is covered in 1/60 of a second, and the rest of the lines are scanned on the second traverse. Thus while the whole picture is scanned 30 times a second each region of the picture receives some light every sixtieth of a second. This practice is referred to as *interlaced scanning*, with a frame frequency of thirty, and a *field frequency* of sixty.

The motion of the electron image past the scanning aperture gives opportunity for each segment of the image to contribute its quota of electrons to the first stage of an electron multiplier, such as is shown in Fig. 4. The surfaces of each of the stages shown are sensitized so as to have a secondary emission ratio of about 2.6 at a velocity of the impacting primary electrons in the order of about 60 volts. This means that the *primary* electrons which get through the scanning aperture, land on the surface of the first stage and cause the emission of secondary electrons therefrom. These are drawn to the second stage (which is 100 volts positive with respect to the first stage) where they in turn act as primary electrons and cause the liberation of secondary electrons from the second stage. On the average each primary electron causes the

Fig. 3. Image dissector tube. (Courtesy of Farnsworth Television, Inc.)

liberation of 2.6 secondary electrons so that the gain of the multiplier is

$$\frac{i_2}{i_1}=S^n$$

where i_2 is the current output, i_1 the input, S the secondary emission ratio, and n the number of stages. Thus an eleven stage multiplier will give a gain of about 36,500.

Sensitivity

The amplification which can be used with a pick-up device is limited solely by the shot noise associated with the statistical variation of rate of photoemission, and the shot and thermal-agitation noises in the first stages of the amplifier. The limit of satisfactory televising is, therefore, that enough light must reach the photoemissive surface to insure that the resultant voltage delivered to the first stage of the amplifier is well above the noise level.

The photoelectric sensitivity of the caesiated photosurface of the image dissector is of the order of 30 to 45 microamperes per lumen. The spectral response peaks at approximately 7500 angstroms, which if combined with the spectral

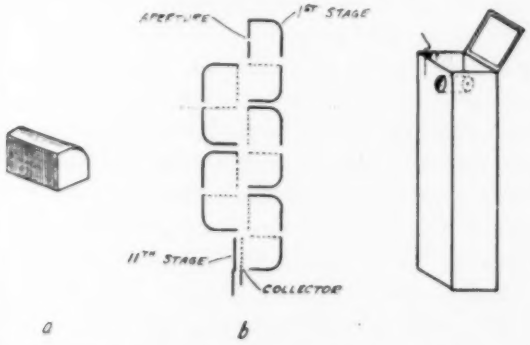

Fig. 4. Electron multiplier. (Courtesy of Farnsworth Television, Inc.)

curve of a tungsten lamp light source results in greatest sensitivity in the infra-red range at approximately 8000 angstroms.

A dissector illuminated with a high light intensity of 200 footcandles will give excellent signals. The current from one picture element with this intensity of illumination is

$$\frac{200\times 0.047\times 37.5\times 10^{-6}}{260{,}000}=1.37\times 10^{-9}\text{ ampere}$$

at the first stage of the multiplier, or about 50 microamperes output current. This current through a 4000-ohm resistor will give a signal of 0.2 volt which is about thirty times the noise level for these conditions. This is a satisfactory noise level for video work. As a matter of fact a

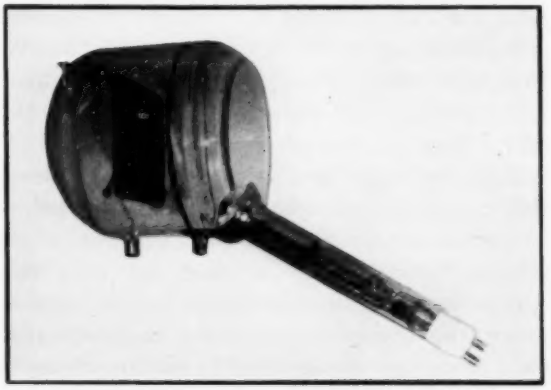

Fig. 5. The iconoscope. (Courtesy of RCA Mfg. Co.)

recognizable picture will be given by a dissector with an average illumination of about 4 footcandles on the photoemissive element; although the effect of noise is evident and the picture appears speckled, the definition is still reasonably good.

The intensity of illumination (I) obtained on the photoemissive surface is given[4] by the expression

$$I=\frac{\pi TB}{4f^2}\cos^4\theta\text{ footcandles,}$$

where B is the surface brightness of the scene in candles per square foot; T is the transmission factor of the lens system used to focus the light on the photoemissive cathode; f is the ratio of the principal focus of the lens to its effective diaphragm opening; and θ is the angle between the axis of the lens and the direction of arrival of the light.

Assuming a figure of $T=0.75$ for a lens of $f:4.5$, and an average angle of 16 degrees for the arrival of the light, $B=40.5I$ so that the dissector requires a brightness of about 150–170 candles per square foot as a minimum.

The Iconoscope

One of the main difficulties in building a single-channel high definition television system is that each picture element is allotted such a

short time in which to release its information. In the discussion of the image dissector it was shown that only those electrons emitted in less than one seven-millionth of a second could be used to effect the reproduction of a single picture element. Since the current associated with the high lights of a comparatively brilliant picture (average of 2000 candles per square foot) is only 1.37×10^{-9} ampere, the charge picked up by the scanning aperture is about 1.9×10^{-16} coulomb. This is only slightly above 1000 electrons; there are even fewer for the shadowed elements of the picture. Looked at in another way only that light falling on a photoemissive surface element during the instant of scanning it is effective. Since there are about 260,000 picture elements and since some time must be allowed for both horizontal and vertical synchronizing, only about one three-hundred-thousandth of the light is effective. The rest is completely useless in sending the picture.

It seems evident that any method which could utilize all the incident light would effect a tremendous gain in sensitivity. The iconoscope[5] does this by storing the effect of the incident light throughout the whole picture and discharging this stored information instantaneously in the scanning process. Naively, the theoretical improvement associated with such a step would seem to be about three hundred thousand. Actually, the use of a storage principal requires that the photoemissive elements be insulated from each other; this fact introduces limitations, so that the realizable improvement is only a small percentage of 300,000.

The photosensitive element of the iconoscope (see Fig. 5) consists of a thin mica sheet ($4\frac{3}{4}''$ wide, $3\frac{1}{2}''$ high, and from 1 to 3 mils thick), which is covered on the back by a solid metallic conducting film and on the front by a vast array of minute photoemissive elements (usually caesiated silver particles). The size of these elements, depending on the manner of forming and sensitizing, ranges from droplets 0.0005 cm in diameter down to submicroscopic particles. A microscopic view of the mosaic is shown in Fig. 6. The solid conducting film on the back of the mica plate is connected on the one hand to the first stage of the signal amplifier (see Fig. 7), and on the other is connected to the sensitized surface by a capacitance of about $100\mu\mu$f per sq. cm, or a total of 0.01μf for the whole mosaic. Since there is no metallic connection to the mosaic, no electron current can flow from the rest of the electric circuit to it.

This mosaic assembly is mounted in an evacuated glass cylinder, the upper face of which

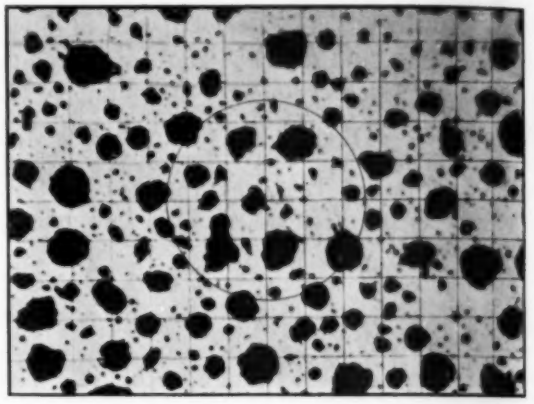

FIG. 6. Microscopic view of photoemissive mosaic. The lines are 0.0015" apart. (Courtesy of RCA Mfg. Co.)

is a clear optical lens through which the optical image is projected onto the mosaic. The arm of the ladle (see Fig. 5) contains an electron gun of the type described elsewhere[6] in this issue. For present purposes the electron gun is simply a source of a beam of electrons about 0.02 cm in diameter (which can be deflected both horizontally and vertically by varying magnetic fields), and a collector ring, which is a high potential anode extending around the inside of the glass cylinder near the junction of the arm holding the electron gun. (Part of the collector ring is shown by the black line in Fig. 5.)

THEORY OF OPERATION

The optical image from the televised object is focused and projected onto the mosaic, causing each element thereof to emit electrons at a rate determined by the intensity of the incident light. These are drawn to the positive collector ring. Since there is no metallic connection to the elements of the mosaic, no compensating electrons can be supplied to the elements; hence they get continually more positive and store the information contained in the optical image.

Somewhere in such a process compensating electrons must be supplied or the element gets positive enough to attract electrons which would otherwise have gone to the collector electrode.

In the iconoscope the ideal method would be to have these lacking electrons supplied by the scanning beam in just the right amount to cancel all those emitted since the element was last scanned. Then the change in charge of each element while under the scanning beam would be the sum of all the photoelectrons emitted during a complete frame period. Since it is this *change* in charge which is transmitted through capacitance coupling to the first stage of the amplifier and, thus, to control the receiver, under this system the control of the receiver brilliance would be the total light received by the corresponding transmitter element during the frame period, instead of only that received during the scanning instant. This would be the perfect working of the storage principle. The signal would be proportional to the incident light, up to the point where the mosaic element became as positive as the collector ring. To accomplish this the electrons in the scanning beam would have to reach the mosaic at very low velocity, since the photoemissive elements are sensitive to high velocity electrons. They will emit secondary electrons when struck with comparatively low speed primary electrons.

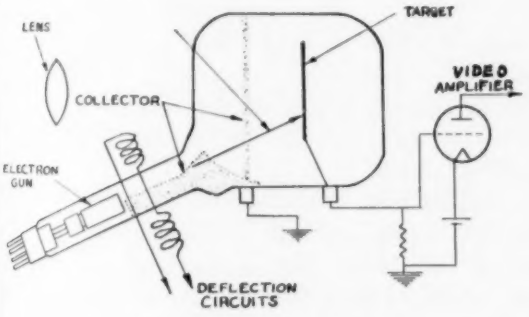

FIG. 7 Iconoscope circuit.

It has been the practice for electron optical reasons to use a positive voltage of about 1000 volts on the accelerating anode and collector ring. Hence electrons strike the mosaic at a high enough velocity to cause an average emission of several secondaries for each primary. The secondary emission ratio in a typical iconoscope is about 5. Under such circumstances the passage of the scanning beam makes the scanned element more positive, rather than more negative. In fact it will be seen later that the element under the scanning beam is the most positive in the whole mosaic.

Whence then can come the compensating electrons which are required to keep the mosaic from continually going more positive? Exactly that which was proposed above happens; the mosaic becomes more and more positive until it reaches practically the potential of the collector ring. It then varies a very few volts above and below this, so that the mosaic is attracting electrons from the space cloud, composed of electrons which it has previously emitted. There is a gentle rain of electrons onto the mosaic; this is not uniform over the mosaic, since the elements were originally charged to *different* potentials by the effect of the incident light. In general each element must on the average regain all the electrons it has lost.

There are thus five separate currents which flow to each element of the mosaic: i_p the current due to photoelectrons leaving the element; i_b the current of the scanning beam; i_s the current due to secondary electrons knocked out by the scanning beam; i_{re} the redistribution current from these secondary electrons; i_{rp} the current due to returned photoelectrons. Of these i_b and i_s are uniform over the mosaic. In order to understand the operation of the tube under these circumstances, it is necessary first to discuss the voltages attained by the elements under special simplified conditions.

Consider the behavior of the mosaic when scanned in darkness. Measurements made on a caesiated silver element set into the surface of a mosaic and connected by a lead coming from the wall of the tube show that the mosaic assumes its most positive potential directly under the scanning beam and its most negative potential directly in front of the scanning beam. At the point of bombardment the surface assumes a voltage of between $+2$ and $+3$ volts with respect to the second anode (collector ring). This potential is, to some extent, dependent on the physical state of the surface of the mosaic, and upon the velocity of the bombarding electrons, but is to a first approximation independent of the current in the scanning beam. This element goes

just positive enough to attract most of the emitted secondary electrons back to it. When the secondary electron current escaping to the collector ring just equals the beam current, equilibrium is established. When the beam passes on it leaves the element at 2 volts positive with respect to the collector anode. The positive element attracts some of the electrons in the space between it and the ring until it becomes so negative as to attract no more. This most negative equilibrium point depends on the geometry of the electrodes and the space density of electrons in the interelectrode space. Hence it is a function of the beam current only. At high beam currents, between 0.5 and 1.0 microamperes, the lower potential will be about -1.5 volts. As the beam current is decreased the spread between the most positive and most negative voltages decreases, since the scanning beam returns to the element before it has collected enough electrons to reach the new equilibrium potential.

If the behavior of the mosaic when scanned in darkness and that when exposed to light but not scanned, are superposed, then the mechanism of generation of picture signal can be described. Fundamentally it is caused by the fact that the potential of an illuminated element of area, just before being scanned, is more positive (or perhaps less negative) than that of one which has not been illuminated. Since the mosaic is driven to the same positive potential regardless of its initial level, charge will be released at a different rate when the beam is traversing the lighted region than it is when scanning an unlighted area. The *change* in current reaching the second anode constitutes the picture signal, since electrons emitted from but returned to the mosaic will not change the charge of the condenser formed by the mosaic and backing plate.

There are several drawbacks to such a scheme which not only limit its effectiveness, but also serve to introduce disturbing voltages into the amplifier. Since the mosaic is approximately at the same potential as the collector ring ($+3$ to -1.5 volts) low velocity photoelectrons do not reach the collector anode, but return to the mosaic. Thus in practice the photoemission is not saturated and only 20 percent of theoretical photoelectric efficiency is attained. Again since the *average* current to the mosaic must be zero, only about 25 percent of the total charge released by an element when struck by the beam will reach the collector anode; the rest will return to the mosaic. As a result of these two factors the working efficiency of an iconoscope is about 5 percent of the theoretical. Since there is a further loss in photosensitivity in not having the whole surface photosensitive the net improvement over a solid surface nonstorage tube is about 10,000 times.

These two factors are affected by the mosaic as a whole. There are others which are controlled by the local fields of the mosaic itself. One is due to the geometry of the system. Even with a solid metal plate in place of the mosaic, maintained at a potential close to that of the collector anode, the current flowing to the collector ring varies with the position of the scanning beam. If the metal plate is made either quite negative or quite positive with respect to the collector anode, secondary emission will be either saturated or suppressed and this spurious signal will disappear. In the actual iconoscope this effect is called *shading* and must be compensated by a special electrical network.

Similarly the fact that certain areas of the mosaic are more positive than other areas causes a local shading effect. More photoelectrons will escape from an element in a shadow when it is near a highly illuminated area than when it is surrounded by other shadowed elements. This results in a local shading effect. A sudden increase in illumination in a given area would cause a change in brilliance in nearby areas and result in a trailer or streamer being attached to the brilliant object.

Another local effect is caused by the fact that the line being scanned is driven positive while under the beam and immediately thereafter. Hence the neighboring lines are subjected to a strong local positive field, temporarily removing photoelectrons and thus increasing the sensitivity of that portion of the mosaic. This phenomenon is called line *sensitivity*. Its effect has been included in the figure of 10,000 given above as the improvement factor of the iconoscope over a nonstorage tube.

Finally, the fact that the electron gun is not on the normal axis of the mosaic, but must be mounted off-center (Fig. 5), introduces a relative

TABLE I. *The brightness of outdoor scenes. (Reference 7.)*

SCENE	LOCATION	TIME (E.S.T.)	DATE	WEATHER	SURFACE BRILLIANCE (CANDLES/SQ. FT.)
Sixth Avenue	New York, N. Y.	9:30 A.M.	4–25–35	Clear	6½
Sixth Avenue	New York, N. Y.	1:15 P.M.	4–25–35	Overcast	40
Times Square	New York, N. Y.	1:30 P.M.	11– 6–34	Light rain	40
Parade	East Orange, N. J.	10:30 A.M.	11–29–34	Light rain	40 to 60
Street	Rockland, Me.	1:15 P.M.	7– 5–36	Overcast	100
Street	Warrenton, N. C.	3:15 P.M.	6–30–35	Clear	130
Street	Harrison, N. J.	3:30 P.M.	8–15–34	Hazy	130
Street	Harrison, N. J.	9:30 A.M.	8–15–34	Rain	16
River	New York, N. Y.	2:30 P.M.	10–24–35	Hazy	50
River	Pennsville, Del.	1:30 P.M.	6–29–35	Hazy	350
Bay	Cape Charles, Va.	10:00 A.M.	6–30–35	Clear	250
Beach	Atlantic City, N. J.	2:00 P.M.	8–18–34	Hazy	500
Football game	New York, N. Y.	1st quarter	11–17–34	Clear	55
		2nd quarter		Hazy	50
		3rd quarter		Hazy	27
		4th quarter			16
		End			2
Baseball game	New York, N. Y.	1:00 to 3:40	9– 8–35	Clear	70 to 100
Snow bank	Harrison, N. J.	10:00 A.M.	1–24–35	Bright sunshine	700
Open field	Bethel, N. C.	3:45 P.M.	7– 1–35	Severe thunder storm	2

displacement at different parts of the mosaic. Were this not compensated for, it would cause the reproduced image to be wider at the top than at the bottom. This effect is called *keystoning*. It is removed once and for all by making the rate of horizontal scanning at the top of the mosaic faster than at the bottom.

RESOLUTION AND SENSITIVITY

Offhand it might appear that the limit of resolution of an iconoscope would be determined by the size of the photoemissive particles. However since the largest of these are 0.0005 cm in diameter and are closely spaced (see Fig. 6) and since the scanning beam is 0.02 cm in diameter there are always a great many droplets under the scanning beam at the same time. With the present standard of 441 lines the mosaic can safely be treated as a two-dimensional continuum. In fact experimentally this is still true for an 800-line picture. Hence while the ultimate limit in definition may be the granular structure of the mosaic, for present practice the limiting factor is the video frequency band allowed.

The iconoscope has sufficient sensitivity to transmit a usable picture of scenes with an average brightness down to 15 candles per square foot. Assuming an f : 4.5 lens of 0.75 transmission this results in 0.37 footcandle on the mosaic surface. While this minimum level can be used to insure program continuity, an average brightness of at least 100 candles per square foot is desirable.

Range of Use of Present Commercial Pick-ups

Comparison of required working conditions with the performance data given above will determine the usefulness of each of these pick-ups. The most stringent requirements as regards illumination conditions occur in outdoor scenes. Table I is reproduced[7] to show representative brightness levels encountered in practice. Changes in brightness levels in outdoor scenes will in general be gradual.

In indoor studios the illumination is limited by the discomfort incident to very high values. A level of 2000 footcandles is easily attainable and does not seriously discommode the actors. Assuming a reflection factor (R) of 25 percent, this results in an average brightness of scene of about 160 candles per square foot ($B=RI/\pi$). Here again changes in brightness level will be gradual.

When motion picture film is scanned illumination levels of 200 footcandles on the photoemissive surface are readily obtainable, so that sensitivity of the pick-up is not the limiting factor. The difficulties of reproducing film are of a different kind. First, sharp changes in scene, and the general illumination level thereof, occur

in the space of one frame. A reproducing device must be instantly responsive to such changes. Second, the standard frame frequency for motion pictures is 24 per second while that for television pictures is 30 per second. Reconciliation between these rates is accomplished by scanning alternate frames three half-times, and the others just the two half-times which are inherent in interlaced scanning.

Since the image dissector requires an average brilliance of scene of about 150–170 candles per square foot for a minimum picture, it is useful for direct outdoor pick-up only under the more favorable conditions (see Table I). However, where the illumination level is sufficient the dissector functions excellently. The only precaution which must be taken with it is that the amplifier gain be adjusted to the range of illumination used. Once set these controls do not have to be touched until conditions are changed. (The receiver controls must be adjusted so that no illumination on the dissector results in no light in the kinescope, but this adjustment does not change when the scene is changed.) Both for indoor studio pictures and for film pick-up this inherent simplicity of operation is very valuable. Since the dissector is a direct coupled device its minimum current is the same for all scenes. Thus the background level of the picture is established, regardless of change of scene. Since there is no time lag in its operation rapid changes in illumination level are readily accommodated. Continuous monitoring is not necessary. Because of the very short time available for changing the picture and the irregularity introduced by the fact that the frame frequency for films differs from that for television, a special projector, in which the film moves continuously and a system of moving lenses changes the picture projected on the photoemissive surface, must be used. A minor difficulty of the image dissector is that it requires about 30 watts power for the scanning system.

The sensitivity of the iconoscope, which can work with a minimum of 10–15 candles per square foot, enables it to pick up most outdoor scenes (see Table I). Its sensitivity is of course sufficient for indoor scenes and film reproduction. The difficulties with the iconoscope arise largely because the photoemissive mosaic is insulated and is discharged by a "rain of electrons," the electrons being the returned secondary and photoelectrons. This makes it subject to spurious signals whose configuration varies with the type of image being televised. Complex shading networks must be adjusted by a monitoring operator during transmission. Also a change in average illumination of the scene requires compensation in the iconoscope, since the photoemissive surface is not directly coupled to the first amplifier stage. These difficulties are not so serious when the change in scene is gradual, as it would usually be in outdoor and studio pick-up. In film reproduction, however, rapid changes in scene are quite usual and close, and continuous monitoring is required to make the iconoscope operate satisfactorily under these conditions, otherwise shading distortion would become excessive. Also the background level must be changed when the type of scene changes. If proper adjustment is made at the transmitter end, no adjustment will be required in the individual receivers. A minor difficulty in the iconoscope is the keystone distortion caused by the placement of the electron gun; this requires a more complicated scanning control, which, however, can be adjusted once for all.

From the above discussion it can be seen that neither device has been developed to the stage where it is ideal under all circumstances, but each has a definite field of usefulness as an element in satisfactory high definition television systems.

Laboratory Developments

The above discussion covers those devices which are already developed to a point of commercial production and usefulness. There are also several promising developments now in an advanced laboratory stage. If the present rate of development continues some of these will be made commercially available in the near future. Among them are:

Two-Sided Mosaic

A mosaic so constructed that photoemission takes place from one side while the scanning beam of electrons falls on the other, offers a means of obtaining saturated photoemission. The mosaic would consist of a fine wire screen (200 to the inch

or more), carefully insulated, with the interstices filled with metal. These metal plugs should be photoemissive on the side on which the light impinges, and secondary emissive on the side which is scanned. Similarly the collector anode which removes photoelectrons should be about 50 volts positive with respect to the mosaic, while the anode which collects secondary electrons should be at about the same potential as the mosaic, so that the effective secondary emission ratio is almost unity. Here the electron gun can be mounted on the normal axis of the mosaic without interfering with the incident light; this eliminates "keystone" distortion. The wire mesh is used as the signal plate.

This tube operates with saturated photoemission but has the same 25 percent efficiency factor because of unsaturated secondary emission that the present iconoscope has. It has several times the sensitivity of a similarly dimensioned iconoscope at low light levels, but redistribution losses limit the maximum signal output. Both local and general shading will still be present.

The Barrier Grid Mosaic

If on the two-sided mosaic just described a shield is added around each individual element, shading and redistribution phenomena can be avoided. One method of doing this is to provide a conducting coating on the beam side, encircling but not touching each metal plug. This barrier grid should be about 50 volts negative with respect to the collector anode for secondary electrons; the elements under the beam will be slightly positive with respect to the barrier grid. Any electron emitted (on this side of the mosaic) from an element must either return to its own element or, if it has sufficient velocity to escape from the local field, go direct to the collector anode. Redistribution and its consequent shading and loss of efficiency are eliminated. Both sensitivity and maximum signal output can be high.

The Conductive Mosaic

If the insulator of an ordinary mosaic is made somewhat conductive, the charged elements can be restored to equilibrium potential by leakage and no returned electrons are required. Thus all problems of redistribution are avoided and saturated photoemission and secondary emission are possible.

Image Amplifiers

The ideal situation in a pick-up tube would be that the light energy would be required to do no work, but only to alter conditions at a point so as to control the magnitude of a stream of electrons. The function of the light would be similar to that of the input voltage of a negative-grid triode amplifier tube. Two methods have been suggested for accomplishing this: one that the light alter the secondary emission ratio of a substance; the other that the light change the potentials of local areas of a two-dimensional grid, which in turn would control the flow of a low velocity electron stream. As yet no practical application of the first method has been developed although there is some indication of its possibility.

Tubes employing the second method have been investigated both at the RCA and at the Farnsworth laboratories. The scheme employed by the Farnsworth laboratories uses a fine wire mesh screen (in one case 400 wires to the inch), insulated on one side but left bare on the other. On the insulated side a photoemissive mosaic of caesiated silver particles is formed by usual methods. The light falling on this mosaic charges the various areas proportionally to the local intensity of illumination. A scanning beam of high speed electrons scans the rear of the screen, causing the emission of a cloud of low velocity secondary electrons. The number of these escaping through the holes of the mesh at any instant depends on the potential of the mosaic in front of the point being scanned. While the high speed primaries (about 20 percent of the total) which pass through the mesh are collected by a fine wire screen which covers the optical lens, the low speed secondaries drawn through the mesh (and probably the photoelectrons) are deflected off to the side and into the first stage of an electron multiplier by a low intensity electric field (the first stage of the multiplier is about 50 volts positive with respect to the mosaic). The photoemissive islands are restored to equilibrium potential by attracting a few low speed electrons

from the cloud available under the scanning beam. They could also be discharged by leakage to the metallic surface on the rear of the screen. The Farnsworth image amplifier has been operated in the laboratory with scenes having an average brilliance of only two or three candles per square foot. Theoretically its sensitivity is much greater.

Acknowledgment

For the benefit of those who have not followed the development of television closely, it may be necessary to state that the author has not been intimately associated with the research work of either of the major groups. He has been asked to write this article simply as an impartial observer. This would of course have been impossible without the complete cooperation of the development engineers of both the RCA Manufacturing Company and of Farnsworth Television, Inc. to whom he freely acknowledges his indebtedness. Dr. V. K. Zworykin, and Messrs. E. W. Engstrom, P. T. Farnsworth, and J. D. Schantz have been particularly helpful. His thanks are also due to Dr. Carl C. Chambers for his careful reading of the manuscript.

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High Definition Television

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EARLY in the development of television it was discovered that the most important technical problem being faced was to make the received picture a sufficiently detailed or well-defined copy of the original to be acceptable. The pictures to which we are accustomed in our daily life contain an enormous total amount of detail. To transmit over a distance the physical information required to reconstruct a picture with sufficiently high definition to reproduce this detail, and repeat this often enough to permit a satisfactory illusion of motion in the reproduced picture, demands a communication system of vastly greater information carrying capacity than anything heretofore used.

As an example, in an early demonstration of "low definition" television between Washington and New York[1] the received picture contained only about as much detail as can be very roughly characterized by a piece the size of a postage stamp cut out of an ordinary newspaper halftone. It was repeated about eighteen times per second. Yet it required, for its transmission, wire or radio facilities capable of handling a frequency band of about 20,000 cycles per second in width, which could have accommodated five standard telephone channels. If a better reproduction of detail is demanded, corresponding to modern standards to be described below, then the band required is several megacycles per second, and the equivalent number of telephone channels is five hundred, or more.

These general considerations indicate very clearly that television requires not only the development of the necessary terminal apparatus, but also presents a major problem of transmission over wire line or radio medium, because it is so very prodigal in the use of this medium. They also indicate, that the element of cost will vitally affect the extent to which any television application may develop.

Because of the importance of this element of cost it is essential that the picture quality to be delivered by any given system be considered carefully. It should correlate with the demands which will be made upon this quality by the use contemplated for the system. The first immediate application of television is apparently developing as a home entertainment, received by radio from broadcasting stations. In the course of time these radio broadcasting stations may be interconnected much as sound program stations are now interconnected. The picture signal is necessarily codified in a number of respects. As in the case of any code, therefore, it is essential to standardize the key to the code if there is to be any generality to the service. Further, this standardization will have to hold for some time if the receiving sets are not to be rendered quickly obsolete. A number of characteristics go to make up picture quality, but of these the one which affects the standardization the most is definition. Hence, this particular characteristic must be settled upon first, with the exercise of as much care and foresight as is possible.

An optical system is essentially a picture transmitting device, forming at one place an image of an object or a previous image which exists at some other place. Such a transmission system is not perfect, in the sense that each geometrical point of the object is reproduced in the image also as a geometrical point, but because of lens aberrations, diffraction and other effects it will instead show as a finite spot of light. Where this spot is a more or less uniformly illuminated and well-defined circle it is called a "circle of confusion." It is to be noted that each individual geometrical point in the object gives rise to its own figure of confusion, which is independent of that given by every other point no matter how close. Thus a given detail in the object is always reproduced with the same imperfection in the image, irrespective of any small accidents in its precise location in the picture.

In view of the fact that the reproduction of picture detail within the dimensions of the figure of confusion is very severely impaired, the size of this figure can be used as an index of the definition of the image. This also characterizes the fidelity, in at least one respect, of the optical transmission system. The size can be given either in actual dimensions, such as inches or millimeters, or in terms of a ratio to the over-all size of the picture. For the purpose of the present discussion the latter is of more interest, since the received picture can be obtained in a variety of sizes.

In the method of printing pictures called the "halftone" process a certain area of the original picture is picked out, its brightness averaged, and this average is characterized by the size of a black dot (in an inverse sense, that is, the greater the brightness, the smaller the black dot) printed on a sheet of paper. The same process is carried out with successively adjacent areas arranged along some pattern to cover the whole picture. It is clear that in this case the exact reproduction of an element of picture detail will vary according to its accidental location in the pattern of areas used in the carrying out of the process. For example, if a fine line runs through the centers of a group of areas it will be reproduced as a row of dots. If, however, it happens to run along the boundaries of the areas in such a group it will be reproduced by two adjacent rows of dots, and will therefore be broadened to a larger extent than in the first case. With such an arrangement the reproduction will in general be somewhat poorer than with the use of the simple optical system having a figure of confusion equal in size to the elementary area used for the halftone process.

In the television process a picture is divided into a large number of adjacent strips each of which in some order of succession is scanned along its length to generate the electrical signal. The signal operates to modulate the intensity of a spot of light at the receiving end, which spot traces, simultaneously, a pattern which is identical to the scanning pattern at the sending end.

Thus it can be seen that along the direction of the scanning line the process is very much analogous to the simple optical system in which the figure of confusion is determined by the scanning and receiving spots and the electrical system joining the stations. Across the direction of scanning the analogy is closer to the halftone process.

A large amount of work has been done in evaluating the definition which may be expected in these two principal directions. From telegraph theory[2] it is found that if information regarding the value of a given number of parameters (which can be assimilated to brightness of successive images of confusion) per second is to be transmitted over the electrical circuit, a minimum frequency band width must be available expressed numerically as half that number of cycles per second. This might be called the "nominal" band transmitting this information. In order to accomplish this transmission restrictions must be placed upon the amplitude and phase characteristics in the transmitting medium to prevent distortion of the signal and consequent loss of some of the information. This loss is not necessarily permanent, for the information may be regained by a suitable correction of the characteristics of the medium by, say electrical networks. These can be inserted at any convenient point up to just where the signal is finally used. When the signal is transmitted as generated the restrictions must hold over the frequency band used. When the signal is used to modulate a carrier they must hold over the width of the two side bands, one of which is formed on each side of the carrier. When one of the side bands is suppressed for single side-band transmission, the requirements hold over the band retained, but there are also additional restrictions to be met.

It has been further found[1] that along the scanning direction the spots at the sending and receiving ends act like low-pass filters to attenuate the higher frequency components of the signal. To determine the effect of the spots in the direction at right angles to the scanning[3] it is possible to analyze the two-dimensional picture as a double series of Fourier terms each of which has two indices. One index gives the harmonic rank along one dimension and the other along the other dimension. When such is done it is found that the effect of the spot is twofold. First it acts as a filter as above indicated, and second it proceeds to generate from some of the components of the original picture new spurious

components, which are added in to the received picture. The attenuation effect occurs both along and across the direction of scanning, but the new components are generated principally from detail showing changes across the direction of scanning. It is indicated that if there is no band limiting in the electrical circuits between the sender and the receiver, then a square spot gives an over-all definition across the direction of scanning which is of the order of half that along this direction. Other studies[4–6] which include the effect of band limiting indicate that with this included and also with other symmetrical spot distributions the ratio is changed from a figure of 0.5 to one lying somewhere between 0.6 and 0.8.

One would expect that in a well-engineered system, the definitions along the two directions would be proportioned to give optimum results. From the general symmetry of most optical instruments (including the eye, if one will tolerate small departures) it might be expected that as a first approximation at least this optimum proportioning would mean equality in the two directions. As has been discussed, this corresponds to a scanning spot slightly longer than it is wide, using a frequency band appropriate to this shape.

Now, however, whenever an engineering optimum is obtained, it means that some quality variable is made a maximum by the proportioning chosen. If the change in the quality variable is continuous and smooth as the proportioning is changed, then there is apt to be quite a range of proportions, on both sides of and near the optimum, where the quality remains very near that at maximum. In terms of the immediate case which we are considering, this means that one may anticipate that the over-all picture quality will not be very sensitive to changes in this distribution of resolutions in the region of the optimum if the product of the two resolutions (itself proportional to the frequency band utilized) is kept constant. It also further means that, over a range at least, the over-all quality of a picture will not be determined so much by the number of lines in which it is scanned as by the frequency band allotted to transmit it. Thus if a given number of scanning lines has been settled upon, it is possible to get increasingly better pictures by using increasingly wider frequency bands for the transmission, and within a range, these will be substantially as good as if the number of lines had been increased in proportion. These conclusions are supported by some experiments at present being carried out, which will be reported upon in detail in due course.

In spite of these observations, it is nevertheless convenient in many cases to characterize the fidelity of detail reproduction of television systems by the number of scanning lines in the received picture simply for the practical reason that this gives a definite figure, whereas the transmitted frequency band may be only vaguely known. This figure is further a design requirement which must be known for the construction of the apparatus.

The early television systems used scanning lines ranging in number around 30 to 50.[1, 2] In the course of time these have come to be realized as too crude to attract sustained interest for general entertainment purposes, and they are now called "low definition" systems. The number of lines used has increased by successive steps, until at the present time most proposals for a home entertainment service plan on something over 400 lines. Such a fineness of reproduction is termed "high definition," the exact line of demarcation being more or less arbitrary. Because of the urgent need of standardization for such a service, the Radio Manufacturer's Association, in the United States, has agreed on a standard of 441 lines.[8] The standard also contains other specifications. For synchronizing the sending and receiving scanning beams, during a portion of the time the signal is divested of picture content and the resulting interval allotted to some suitably shaped pulses to carry out this function. Similarly in order to permit easy selection of these pulses the range of amplitudes which they take up in the signal has also been divested of picture content. Another specification in this standard relates to the order in which lines are scanned, this being for the purpose of reducing flicker. The specification in the first place calls for 30 complete picture repetitions per second. With the lines scanned in natural sequence this gives a pronounced flicker. If, however, the odd-numbered lines are first scanned in sequence, then the even-numbered, successively alternating in this fashion, the entire field will be covered

coarsely every sixtieth of a second. Thus areas of appreciable size on the picture have a flicker rate of 60 per second instead of 30. This process is known as "interlacing," and forms part of the standard.

No specification is placed in the standard on the frequency band width of the signal, but the carrier frequency allocations which are set permit a single side-band width up to as much as four megacycles or so, which corresponds to the nominal range for a square scanning aperture. For equal resolution along and across the scanning lines, the frequency band required is, however, generally estimated as a little less than three megacycles. Although the picture quality is improved as the frequency band width is increased, it is important to note that cost and crowding of the ether are also increased. It therefore seems wise to avoid setting a rigid frequency band requirement until more is known about costs of the several parts as well as the capacity of the industry to support these costs.

It is not expected that the standards referred to above will permit of a picture comparable to that obtained with professional 35-millimeter motion picture projection. If, however, the other characteristics of the picture, such as results of signal distortion within the band specified, fidelity of contrast reproduction, geometrical distortion of the image, etc., are engineered to a refinement consistent with the definition, the resulting picture can be expected to meet the needs of home entertainment with a considerable degree of satisfaction. Much in the same way home motion pictures, in which the element of cost also has some importance, give considerable satisfaction in their field with a definition less than that of the professional pictures.

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Problems of Television Transmission

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IT HAS been established empirically as well as mathematically that for present day standards of television—441 lines, 30 frames per second and a picture ratio of 4 : 3—a maximum frequency of between 4.25 and 4.75 Mc is needed in order to obtain horizontal definition approximately equal to the optimum value of definition in the vertical direction.

Single side-band transmission standards make it possible to locate most of this frequency band within one television channel. Fig. 1 shows a typical channel where slightly over 4 Mc are available for the picture signal. To produce television signals containing frequency components up to and above 4 Mc without appreciable amplitude and phase distortion requires carefully designed studio equipment. Assuming that adequate resolution is furnished with the optical system reproducing the image, the iconoscope, dissector or other type of electronic pick-up devices used in the studio or for film transmissions must have a scanning spot of the correct size. Even then, due to the finite size of the iconoscope spot or the dissector scanning aperture, so-called aperture correction has to be applied in order that a black and white optical test chart, the highest detail of which should correspond to 4.5 Mc, will produce video signals of equal amplitude within that range. It is to be noted that aperture correction at the transmission end does not allow for the existence of an aperture effect at the receiver, such modification of the video signal amplifier being a part of the receiver design.

Though it might not seem obvious, extremely accurate synchronization is an important factor in obtaining the highest possible definition within a given frequency band. Inaccurate timing of the synchronizing pulses in the horizontal, or especially the vertical direction, would eliminate much of the fine detail at either the transmitting or the receiving end, or both, wherever synchronizing difficulties arise.

Figure 2 shows a block diagram of a typical television studio film channel. The individual units are so marked that the diagram should be self-explanatory. After the video and synchronizing signals have been combined and suitably amplified, they enter the last unit in the studio equipment which is a line amplifier. This terminates in an impedance equal to the surge impedance of the coaxial cable connecting the studio equipment with the transmitter. The coaxial cables most frequently used have a surge impedance in the neighborhood of 70 ohms and require equalization in order to compensate for the losses within the cable.

The amplitude *versus* frequency characteristic for an unequalized 70-ohm cable over a distance

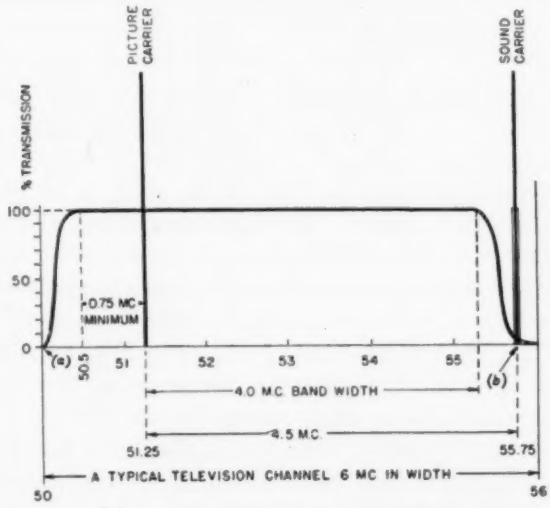


FIG. 1. Transmitter amplitude characteristic (vestigial side band transmission). As indicated at (*a*), transmission at lower edge of channel is not greater than 0.1 percent and as indicated at (*b*) transmission of picture side band at sound carrier also is not greater than 0.1 percent.

of one mile is given in Fig. 3. When equalized, the amplitude characteristic is substantially flat up to 8 Mc. The noise level of such a short coaxial link without a repeater is mainly represented by 60-cycle hum as well as a certain amount of 120-cycle and even 180-cycle harmonics thereof.

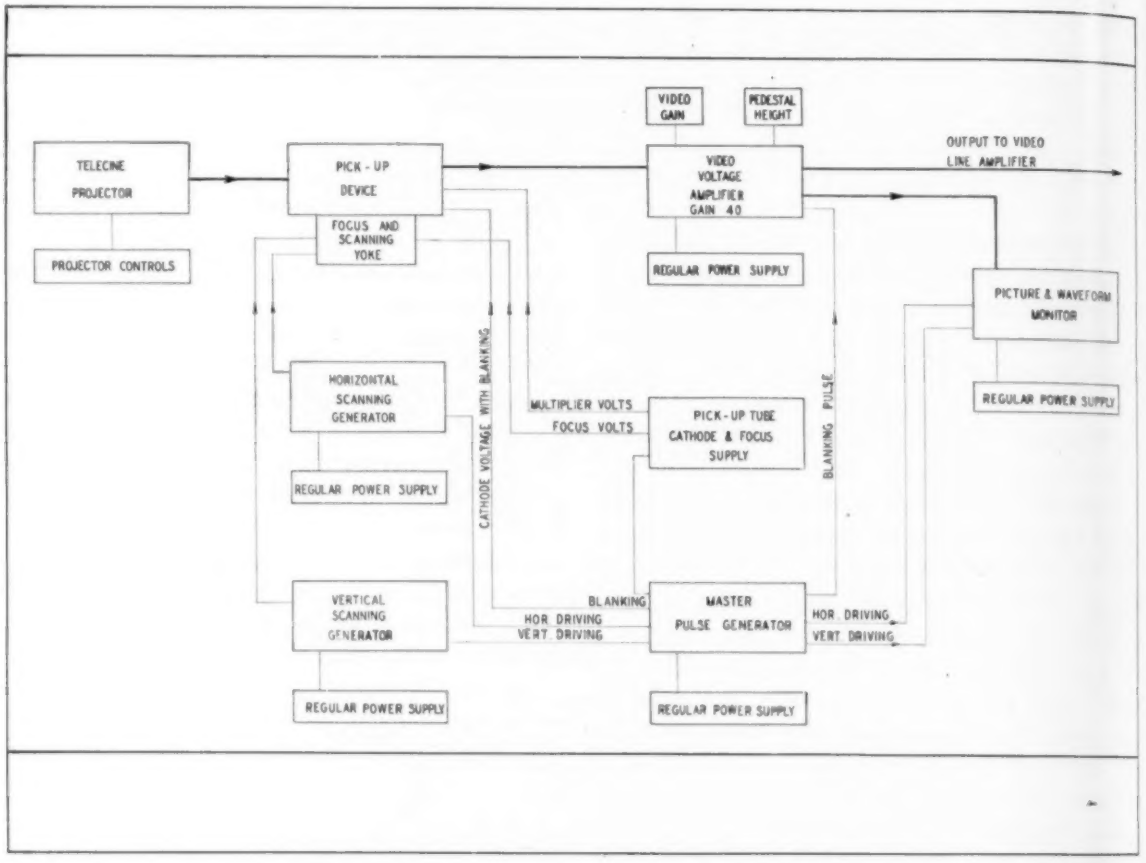


FIG. 2. Block diagram of a typical studio film channel.

The average noise level is of the order of 60 db above one $\mu\mu$watt, though this value varies greatly from one installation to another. Correspondingly, a signal input of not less than 90 db above one $\mu\mu$watt should be impressed across the cable. The traveling time of all frequencies within the desired band must be compensated for so that the phase angle *versus* frequency curve becomes a straight line going through the origin, which means that the phase displacement must be proportional to the frequency.

Once the video signal is available at the transmitter, a final check up with the picture monitor and wave shape oscilloscope determines the available definition and phase correction at the input of the transmitter. It will be found that with present day equipment a video band of 5 Mc can be forwarded from the camera to the input of the transmitter without noticeable deterioration.

There are several types of modulation methods employed in television transmitters. One method, most universally adopted, is grid modulation of the power amplifiers. Another method, which is just in the process of being tried out, consists of modulating the carrier at a low level, at the same time attenuating the lower side band with suitable filters. The modulated carrier envelope, which corresponds to Fig. 1, is raised to a level of several kilowatts using linear amplifiers with wide-band interstage couplings. This method makes more efficient use of the maximum output available at the power amplifiers. The third method, called "transmission line modulation,"[1] impresses modulation across the transmission line between the power amplifiers and the antenna. In practice a one-quarter wave line, terminated in the output of the final modulation stage, is connected across the transmission line. It is claimed that this system is efficient and has the capacity for a high degree of modulation.

The block diagram of a typical grid-modulated television transmitter is shown in Fig. 4. In the

design of such equipment great care has to be exercised. The gain of each stage, it is known, is roughly inversely proportional to the band width it has to amplify. Thus capacities of circuit elements to ground and interelectrode capacities must be kept as low as possible. For good low frequency response the power supplies must have extremely small and constant impedances.

In Fig. 4 it is indicated that between the third and fourth stage, fourth and last stage of the modulator, as well as between the output of the latter and the grid of the power amplifiers, a so-called constant resistance network serves as a

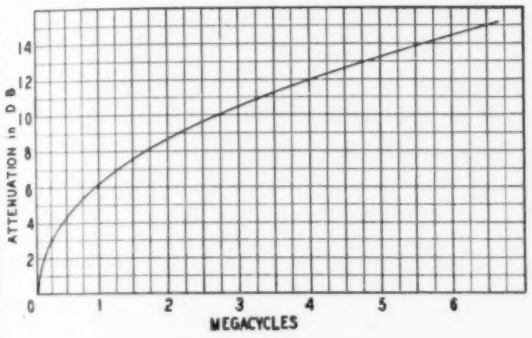


FIG. 3. Attenuation per mile of an unequalized 70-ohm coaxial cable.

coupling. The purpose of this constant resistance network is primarily to provide a load resistance constant for frequencies from 0 to 4 Mc. The principle of this filter is explained in Fig. 5 where the elements are so proportioned that at all frequencies this filter represents a pure resistance equal to R_1. The same holds if the filter is connected as shown in Fig. 6, which is the fundamental circuit of the constant resistance network employed by the modulator stages of Fig. 4. Another advantage of such a network is that the capacities of the first sections which are next to the plates of the preceding tube are smaller than the capacity of the equivalent load resistor.

The final form of the constant impedance network as shown in Fig. 7 results in a resistance, constant over the desired frequency band and equal to R_2 between plate and ground and a constant resistance of R_4 between the plate and the following grid.

The d.c., or picture background component contained in the signal, is reinserted at the grid of the fourth and at the last modulator stage with the aid of the $1-V$ diodes. The diodes act as peak detectors with respect to the synchronizing pulses and vary the grid bias of the modulator stage in such a way that the peaks of the synchronizing pulses correspond substantially to identical grid voltages. Fig. 8 shows a combined television signal after the d.c. component reinsertion, consisting of synchronizing, blanking and picture components. Note the resemblance of such a television signal to the old-fashioned telegraph signals.

The plate of the last modulator stage consisting of two 891's is directly coupled to the grids of the power amplifier tubes. Since no d.c. component reinsertion takes place between the last modulator stage and the power amplifier grid, a

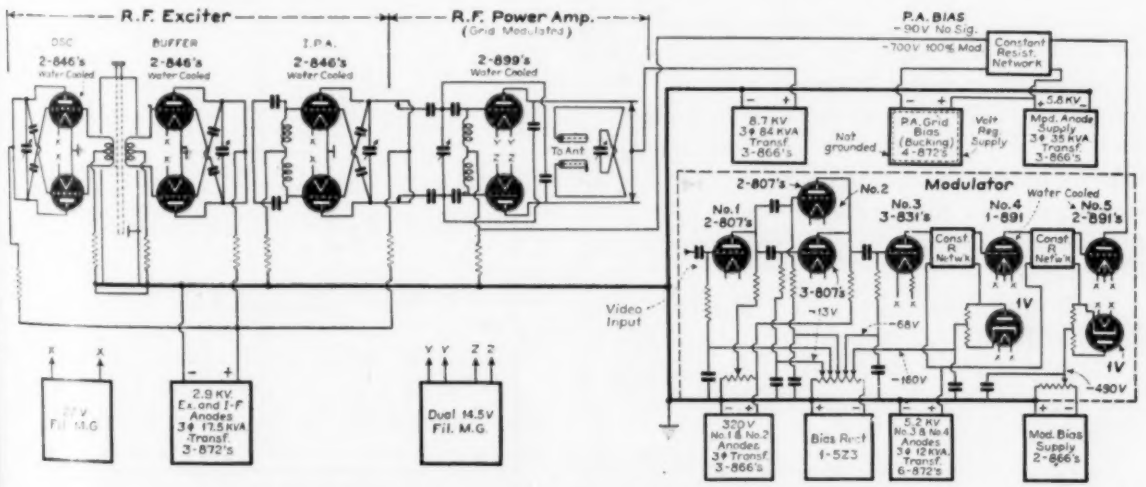


FIG. 4. Block diagram of a typical grid-modulated television transmitter.

direct coupling is provided combined with another constant resistance network similar to those described before.

In the typical transmitter under discussion, a master oscillator with a temperature compen-

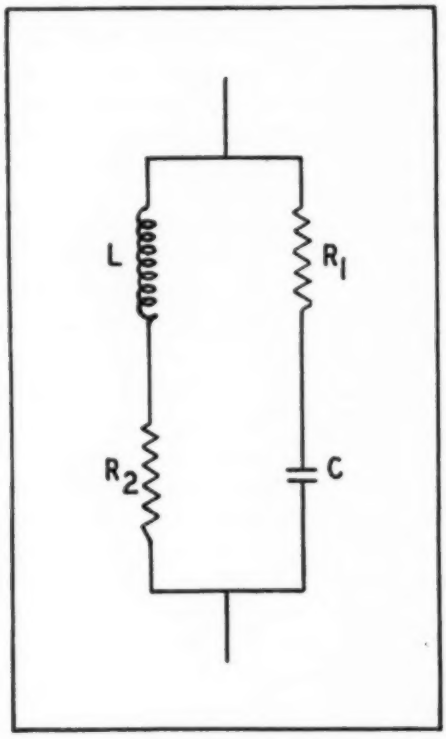


FIG. 5.

sated grid line and two 846 tubes as oscillators keep the carrier frequency constant within 0.02 percent of its value. A buffer stage and an intermediate radiofrequency amplifier precede the power amplifier which dissipates approximately 27 kilowatts per tube. The maximum available radiofrequency power from such an ultra-high frequency wide band transmitter is limited by such factors as neutralization and capacitive losses, limited filament emission, leakage current losses and heat dissipation. About 15 kw peak radiofrequency power is available from one pair of 899 tubes.

Since the transmission of a 4 Mc wide video signal within a 6-Mc frequency band can only be accomplished by single side-band transmission, a filter has to be provided which will suppress one of the side bands.

This filter consists of two main sections, the side-band attenuation filter and the so-called notch filter. The function of both is indicated in the transmission characteristic given in Fig. 9. The combination of the two curves is such as to conform to the desired carrier envelope shown in Fig. 1.

Careful design is needed in the construction of the antennas themselves. The radiators must have a substantially flat impedance over roughly a 5-Mc band. It has been found that a signal strength of about one mv per meter at the receiver will produce an acceptable signal to noise ratio in most locations. The direct sight range of a transmitting antenna which is 1000 ft. above the ground is of the order of 40 miles. This can be extended if the receiving antenna is raised sufficiently above ground.

Roughly 25–30 kw of radiofrequency power would be needed in the transmitting antenna to produce such signal strength at such distances. A certain amount of power gain can be obtained by suitable antenna design, as shown in Fig. 10. Here an approximate power gain of 3, 5 : 1 over a pair of crossed dipoles can be obtained by

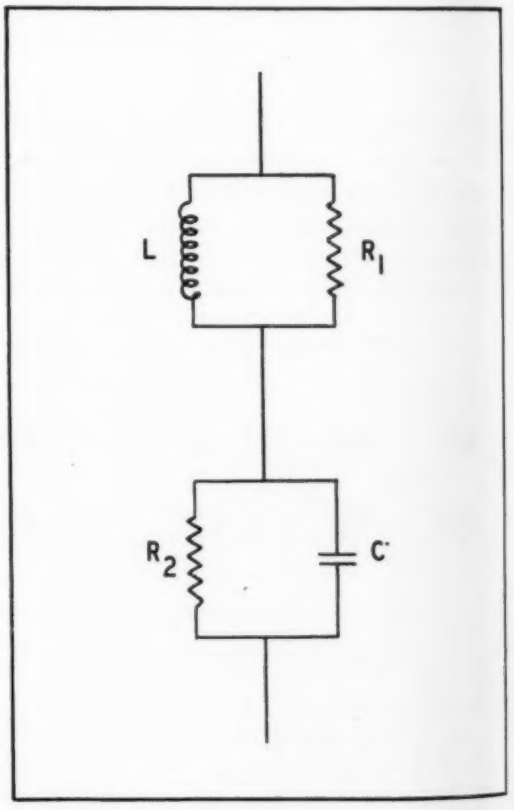


FIG. 6.

stacking two sets of horizontally polarized dipoles on top of each other, one-half wave-length apart.

The antenna should be connected to the transmitter through a low impedance transmission line of the order of 35–70 ohms.

In such a line high quality insulators must be employed in order to reduce dielectric losses. Either a single transmission line or a balanced pair of lines suitably coupled to the power amplifier tank circuit can be used.

Ordinarily dipole radiators, if rigidly constructed to withstand high wind velocities, would not possess such characteristics without suitable correcting sections having capacitive and inductive branches. In Fig. 10 such sections are indicated, located one-half wave-length behind the dipoles and inserted in each branch of the concentric feeder. The radiation characteristic of a dipole arrangement as shown in Fig. 10 is indicated in the field strength diagram (Fig. 11). If the dipoles were crossed, a circular pattern would result (dotted lines). However, in the present arrangement a compromise must suffice.

An important problem in the process of transmitting television signals is the question of

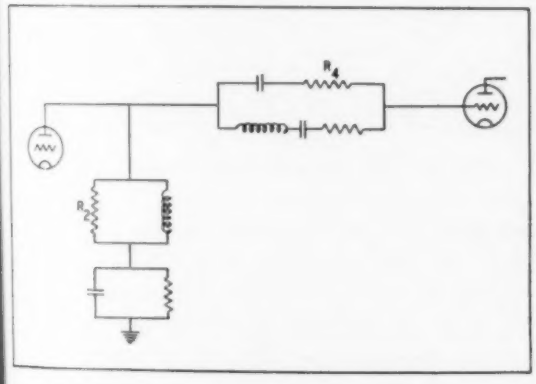


FIG. 7.

propagation characteristics of the carrier frequency used.

Figure 12 shows a diagram representing the attenuation curve of a typical frequency within the lower television band. The actual field strength figures refer to a radiated power of 1 kw. The attenuation of the carrier will decrease with increasing distance according to a curve which lies in between the inverse square and the inverse distance law. In this particular case the transmitting antenna was 1000 ft. above ground and the receiving antenna 70 ft. above ground, thus a direct signal could be received at a distance of 50 miles from the antenna.

It is interesting to note that starting from a certain minimum antenna height and the corresponding minimum line of sight distance, the field strength at the horizon remains substantially constant when the antenna height, and accordingly the distance between antenna and horizon, are being increased.

Figure 13 represents a curve where the field strength in mv/meters is plotted against antenna

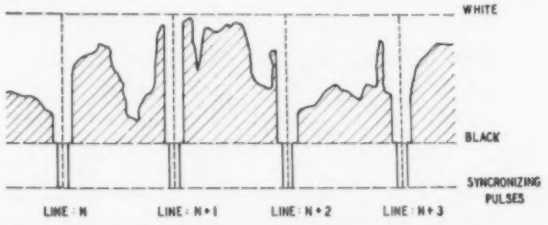


FIG. 8. Representation of combined television signal.

height and the corresponding maximum line of sight distance in miles to which the field strength figures refer.

It is a well-known fact that ultra-high frequencies of the magnitude used in television transmission are of quasi-optical nature and therefore subject to reflections from buildings or other solid objects, especially from metal structures. The multiple transmission paths which thus occur can produce multiple images in the receiver. At present the only remedy for this disturbing phenomena is suitable orientation and location of the receiving antenna. In certain receiver locations it might happen that the reflected signal is of far greater amplitude than the direct signal, in which case satisfactory reception can occur.

Let us assume that a receiving point is located not too far beyond the horizon. The conditions for reception then will depend on several factors. For cases where there is flat land between the receiver and the transmitter so that the waves strike the ground at grazing incidence, they will be reflected at fairly high efficiency but with a 180-degree phase reversal. Thus the received signal is a resultant of the ground wave reflected from the ground and the original wave. Both the

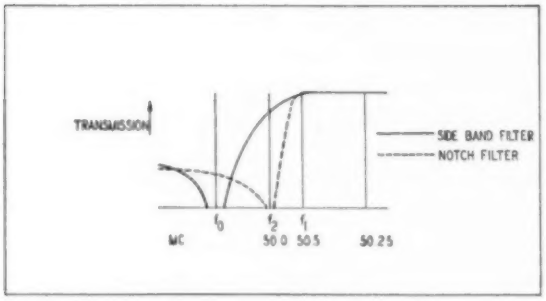


FIG. 9. Transmission characteristic of side-band attenuation filter and the so-called notch filter.

direct and the reflected ray will arrive at the receiver at approximately equal intensity but practically out of phase. For flat ground the phase difference between the two will be—

$$\phi = 4\pi \frac{h \cdot H}{\lambda \cdot D}$$

where H is the height of the transmitting antenna, h the height of the receiving antenna (both above ground), λ wave-lengths in meters and D distance between transmitter and receiving antenna. The direct field strength from a half-wave dipole is—

$$E_0 = 7 \cdot \sqrt{W}/D$$

where W is the power radiated in watts.

Therefore the resultant field will be—

$$E = E_0 \cdot \phi = 88h \cdot H\sqrt{W}/\lambda \cdot D^2.$$

As can be seen this phenomena follows an inverse distance square law applicable only for grazing incidents over flat land, free from obstructions. If the transmission were to take place between two highly elevated points, the path difference would be more than a fraction of one wave-length and the above equation would not hold.

According to Fig. 12 the field strength of an ultra-high frequency carrier in the neighborhood of 40 Mc decreases somewhat less rapidly than the inverse square of distance law. This, of course, holds only within the optical range. Beyond the horizon the field strength decreases nearly as the fourth power of the inverse distance. The diffracted wave progressing beyond the horizon will create a constant field strength at a not too distant receiving point while the refracted wave will vary in intensity and will be subject to fading.

The attenuation beyond the horizon increases rapidly with increasing frequencies. At about 400 Mc the attenuation in decibels at a given point will be roughly three times that at 30 Mc.

With regard to polarization of a carrier within the present television channels, there is little choice between horizontal and vertical direction as long as the transmission takes place over land. It has been found, however, that over water vertical polarization is to be preferred.

Transmission of a 4 Mc wide video signal over distances of the order of several hundred or

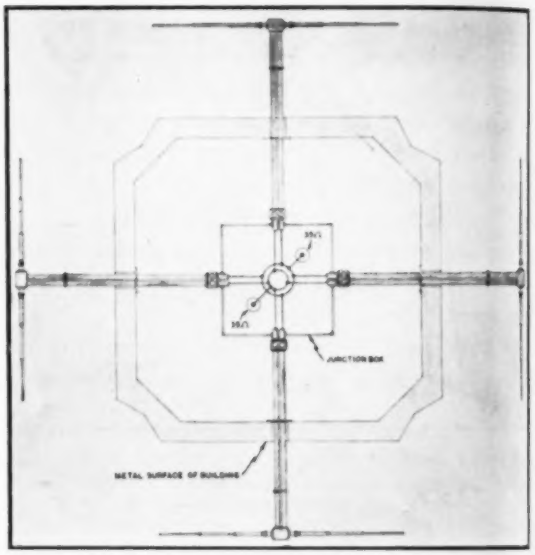


FIG. 10. Antenna designed for television.

even several thousand miles presents a number of difficulties, which from a theoretical viewpoint, however, do not appear to be unsurmountable.

Several possibilities lie open for such long distance transmission. The first would require the use of carriers below 40 Mc so that a reliable skywave reflected from the ionosphere could be received as in the case of long distance ultra-high frequency phone communication. One serious objection to this method is the occurrence of multiple images which are caused when signals travel along several paths of unequal lengths.

A displacement between two images of about one picture element (one-line width) corresponds to a time delay of roughly $\frac{1}{4}$ microsecond. The velocity of the carrier being about 187,000 miles per second, then the path difference correspond-

ing to $\frac{1}{4}$ microsecond would be $187{,}000 \times 0.25 \cdot 10^{-6}$ mile or approximately 1/20 mile.

If distances of the order of several hundred miles are involved differences in path length of such low value is easily conceivable. In practice results of skywave transmission of a wide band television signal over the Atlantic have been observed and photographed.[4] Most of the pictures consist of a number of displaced images superimposed on top of each other.

Another severe obstacle which renders the skywave transmission of wide band television signals impractical is the frequent occurence of selective fading phenomena. Especially serious fading conditions arise in the lower television channels near the frontier of possible skywave transmission where the ratio of carrier frequency to modulation band width is relatively large, of the order of 10 : 1 as compared with sound transmission with a ratio of 10,000 : 1 on similar carrier frequencies.

When considering the use of the coaxial cable as a means for long distance television transmission, as for television network operation, it is necessary to examine conditions as they exist in the New York-Philadelphia coaxial run.

This system in its latest form employs a carrier in the 300-kc region which permits the transmission of a 2.5-Mc side band at a peak frequency of 3 Mc. Essentially it is a single side-band transmission system with a vestigial side band on the lower side of the carrier. Repeaters have been installed halfway between those used for the one-Mc band transmission and are approximately five miles apart, which means that per 1000 miles, 200 repeaters would be needed for a 2.5-Mc band. Employing the same system for a 4-Mc band, repeaters would have to be spaced even closer. It is uncertain yet whether the method of merely increasing the number of repeaters will lead to the solution of the problem of coaxial cable transmission for a 4 Mc wide television signal.

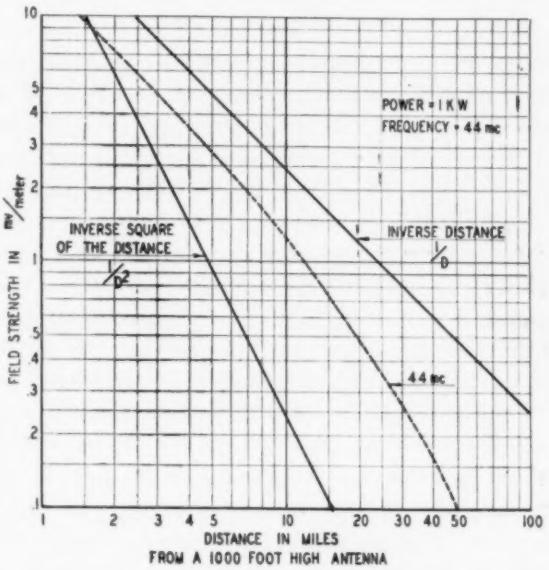


FIG. 12. Attenuation curve corresponding to a typical frequency in the lower television band.

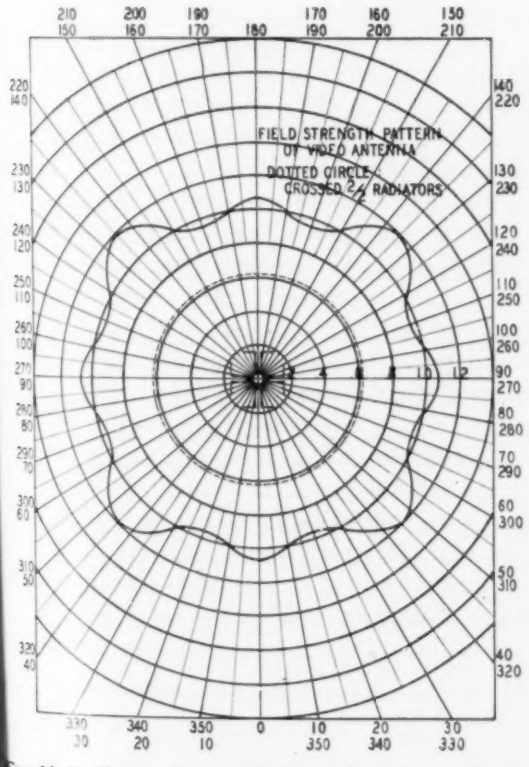


FIG. 11. Radiation characteristics of the antenna shown in Fig. 10.

At present more promising prospects for long distance television transmission seem to lie in the field of ultra-high frequency relay transmissions. Considering frequencies of the order of 300 Mc the problem of concentrating such waves into a narrow, well-directed beam is greatly reduced over similar problems occurring in the lower television channels.

Let us suppose that two relay antenna towers, each elevated 500 ft. above ground, would have

no high obstructions between them. If h_1 and h_2 are the height of the towers above ground in feet, then the maximum line of sight distance in miles between these two towers will be—

$$D = 1.22(\sqrt{h_1} + \sqrt{h_2}).$$

In the present example D would be 55 miles. For such purposes a transmitter power output of 50 watts would probably be adequate. It is to be expected that transmitters operating on one meter or less, modulated with a 4-Mc signal, can be constructed to supply power of about 50 watts concentrated into a narrow beam. Such relay receiving and rebroadcast stations could be operated automatically, or rather controlled from a remote point, so that the least necessary expense would be connected with their upkeep.

Let us consider the number of channels necessary in order to cover a distance of, say, 1000 miles. As indicated before, two towers each 500 ft. high can be placed approximately 55 miles apart and still be within line of sight provided no obstructions are in between them. It also has been indicated that the attenuation of frequencies beyond the horizon, around 400 Mc, is appreciably higher than that of frequencies of the order of 50 Mc. Therefore it would be safe to assume that two 6 Mc wide channels alternated between successive relay stations would be sufficiently practical from an interference point of view.

For instance, in Fig. 14, T represents the original transmitter, A the first relay station at 50 miles distance. The television signal which would be radiated from T on a television broadcast channel can be received at A and converted into a carrier modulated between 300 and 306 Mc and directed towards relay station B. Here the relay beam is received and converted to a carrier which is modulated between 320 and 326 Mc. At station C the first relay frequency band (300–306 Mc) would be repeated again.

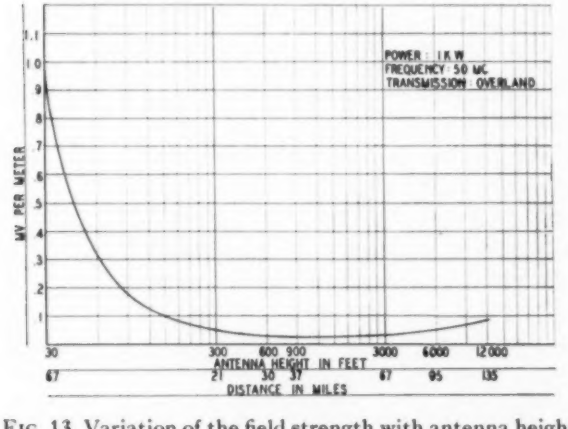


FIG. 13. Variation of the field strength with antenna height and the corresponding maximum line of sight distance.

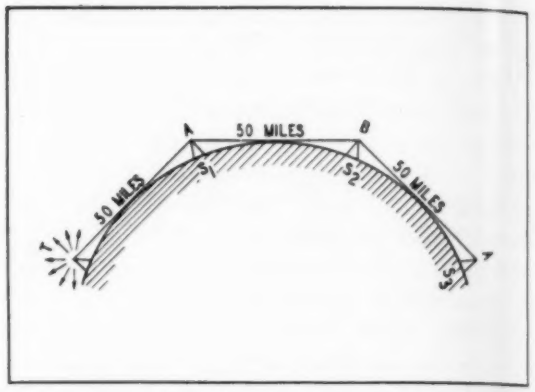


FIG. 14. Diagram to indicate the transmission of television signals by relay stations.

To cover a distance of 1000 miles, 20 such relay stations would be necessary using only two television relay channels. There are not sufficient experimental data available to determine whether actually the same two channels could be repeated at distances of 100 miles. Should interference between two relay stations using the same frequency occur, a third channel might easily be introduced so that interference could only take place at distances of 200 miles.

It is conceivable that at wave-lengths below one meter, as employed in relay service, frequency modulation could be used to some advantage. Though greater channel widths would be required than are used at present for an amplitude modulated television band, the substantially reduced interference area might possibly make up for this. In any case, if one were confronted today with the task of transmitting a 4 Mc wide television band over distances beyond the horizon there would probably be no choice in the matter but to use ultra-high frequency relay stations, as the present state of the art offers no other means of long distance television communication.

[1] W. N. Parker, "A Unique Method of Modulation," Proc. I. R. E. **26**, 946 (1938).
[2] J. H. Morecroft, *Principles of Radio Communication* (1921), p. 807.
[3] H. H. Beverage, "U. H. F. Propagation," RCA Review **1**, 76 (1937).
[4] D. R. Goddard, "Skywave Transmission Above 40 Mcs.," RCA Review **3**, 309 (1939).

Television Receiving and Reproducing Systems

BY E. W. ENGSTROM

RCA Manufacturing Company, Camden, New Jersey

AN IMAGE of a scene to be transmitted by television may be regarded as a variation of brightness with respect to geometrical position on a plane. For transmission, the variations in brightness are converted into variations in electrical current with respect to time properly positioned with respect to certain reference signals. The resulting current, combined with the reference signals, modulates in amplitude a radiofrequency carrier.

At the receiver the radio signal is intercepted and amplified, and then from it the original variations in electric current are retrieved. These are used to synthesize an image of the original scene. Image reproducing methods may be divided into two general classes: electronic, with the cathode-ray tube as the primary example; and electro-mechano-optical. Emphasis will be placed in this discussion on the cathode-ray tube method because it appears to hold greater promise for home television.

For a broadcast type of television service, adequate coverage of a service area is the prime consideration. The frequency of the radio carrier must be high enough to permit transmission of the relatively wide side-bands which are required, and so high that reflections from the ionosphere will not regularly occur. The second requirement is necessary to prevent multiple images caused by reflections from the ionosphere, and to permit duplication of frequency assignments with reasonable geographical separation of stations on the same channel. Further, in television high signal strength is required at the receiver locations. Thus, the radio carrier must be at such a frequency as to permit generation of adequate power. The carrier frequency must be such that the attenuation caused by obstacles on or near the transmission path is not too great, and such that the shadows cast by obstacles are not too sharp or too dense. All these considerations point to frequencies above and near 40 megacycles, for example, 44 to 108 megacycles.

An advantageous channel arrangement for television is one such that each transmission channel is complete within itself; that is, such that each channel provides for transmitting the video,* synchronizing and accompanying sound signals. In such a system, the video signals and synchronizing signals may be transmitted on one carrier and the sound signals on another carrier. (The video and synchronizing signals are transmitted alternately.) One advantage of locating these two carriers close together in frequency within a single channel is that then they will have nearly identical propagation characteristics. With a fixed separation between the sound and picture carriers within each channel simplified receiver operation can be obtained and a single control of receiver tuning is possible.

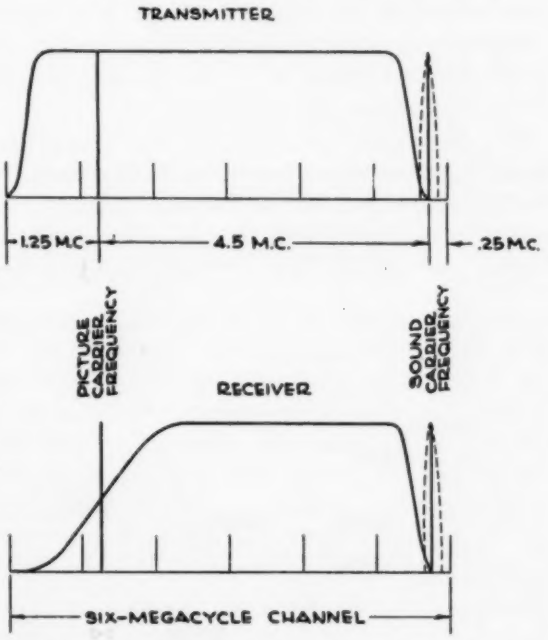


FIG. 1. Selectivity characteristics of transmitter and receiver.

It has been found that the picture carrier and sound carrier should be of approximately the same power. This requirement is determined by

* Video frequency is the frequency of the voltage resulting from television scanning.

considerations of receiver selectivity for separating the picture and sound signals and by considerations of the effects of noise interference on the reproduced image and sound.

As the number of scanning lines in the television image is increased, the frequency band required for transmission also is increased. Thus, practical limits are encountered in amplifiers and transmission methods. The most definite limit is probably the frequency space available in the

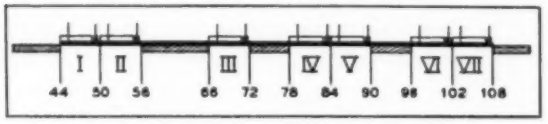


FIG. 2. Television broadcast channel allocations.

radio spectrum for television channels. Experience indicates that an image of about 400 lines will provide satisfactory performance for home type television entertainment and will require equipment characteristics which can be obtained in practice. A standard of 441 lines has been recommended for the United States.

The frequency band required for a television image is proportional not only to the amount of detail transmitted, but also to the rapidity with which it is transmitted, that is, the number of frames per second. The frame frequency and field frequency* (for interlaced scanning) are determined by the allowable flicker of the image and by the power supply frequency. To reduce the visual effects of a.c. ripple in the reproduced image, the field frequency should be a multiple or submultiple of the power supply frequency. For example, a frame frequency of 30 per second is satisfactory for a power supply frequency of 60 cycles per second. In order to have satisfactory conditions with regard to image flicker, an effective frame frequency of 50 or more per second is required. This may be obtained without an increase in band width by using interlaced scanning. By this method, odd numbered lines are scanned first and then the even numbered lines, with two fields of scanning for each frame. Frame and field frequencies of 30 and 60 per second, respectively, are satisfactory and are standard in this country.

The corresponding standard television channel is 6 megacycles wide with a spacing between picture and sound carriers of 4.5 megacycles. Such a channel arrangement is shown diagrammatically in Fig. 1.

It has been found that better performance in terms of picture detail for the given 6-megacycle

* Field frequency is the number of times per second the frame area is fractionally scanned in interlaced scanning.

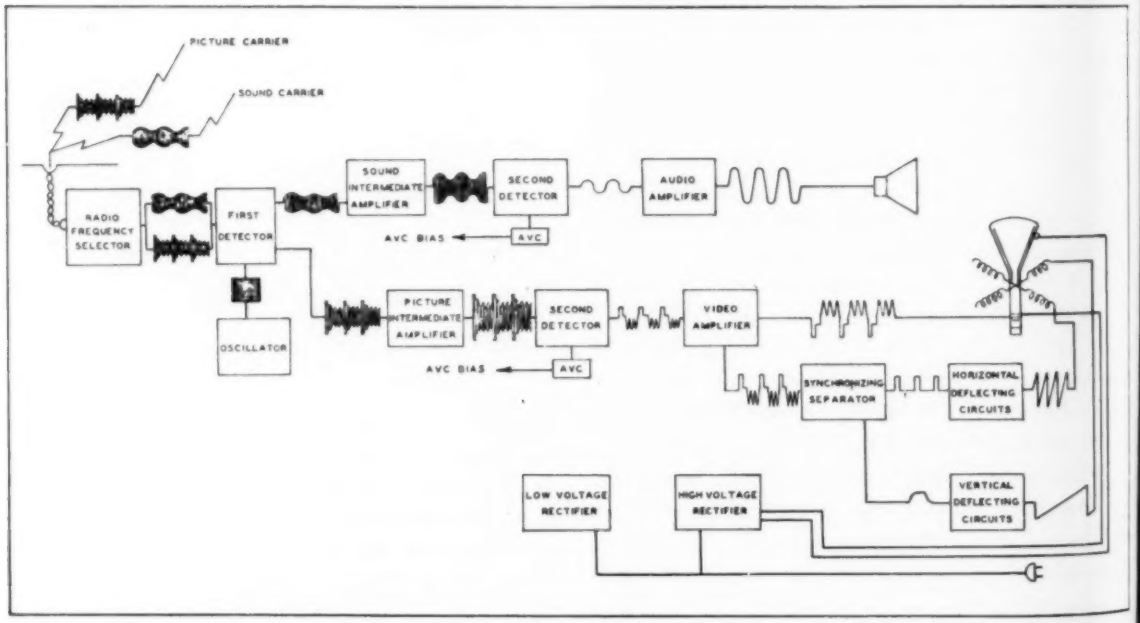


FIG. 3.

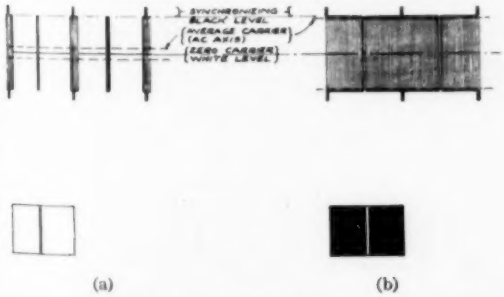
channel is obtained if part of one side-band is suppressed at the transmitter to permit a wider frequency band in the other side-band.** Thus, in Fig. 1 there is space available for at least 4-megacycle side-bands on the high frequency side of the carrier, while the lower frequency side-band is completely attenuated in approximately 1.25 megacycles. The sound accompanying the television picture is transmitted on a separate carrier 4.5 megacycles higher in frequency than the picture carrier.

The lower frequency group of channels allocated to television broadcasting are shown in Fig. 2.

Radio Receivers for Television

In the television receiver the picture and sound signals must be received and utilized simultaneously. The band width of the picture part of the receiver is many times greater than that required for the sound part. For simplicity of operation, uni-control tuning for picture and sound is preferable. A superheterodyne circuit is well suited for meeting the receiver requirements. The picture and sound carriers in all television channels will have the same frequency separation. Therefore, by properly choosing the pass bands of the two intermediate frequency amplifiers, both carriers may be heterodyned by the same oscillator. The picture intermediate frequency must be high because of the extremely wide video frequency band.

In order to obtain a flat over-all video response while utilizing the vestigial side-band system, it is necessary to make the over-all selectivity of the picture part of the receiver have the proper shape, illustrated in the lower part of Fig. 1. This curve shape is such that the carrier falls at the point of 50 percent response. For very low video modulation frequencies the responses to the two side-bands are nearly equal. As the video frequency increases, the response to one side-band increases at the same rate that the response to the other decreases, until at about one megacycle the response to the upper side-band is 100 percent and that to the lower side-band is zero. Beyond this frequency the response to the upper side-band is nearly constant up to cut-off, which is about 4 megacycles from the carrier.



(a) (b)

FIG. 4. Television signal with "d.c. transmission." (a) For predominantly white picture. (b) For predominantly black picture.

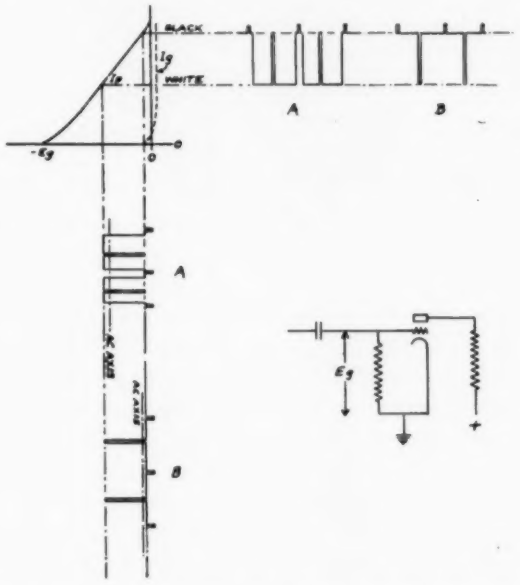


FIG. 5. Circuit for restoring the d.c. component to the video signal.

Figure 3 is a block diagram of a typical receiver, showing the functions of the various parts of the circuit, and indicating the wave shapes occurring in them. Since both sound and picture are to be reproduced by this receiver, it is desirable to use a single antenna for picking up both carriers. Both signals are passed by the radiofrequency circuits to the first detector where they are heterodyned to intermediate frequencies by the local oscillator. These signals now comprising two bands of intermediate frequencies are amplified through their respective intermediate frequency amplifiers and rectified by separate

** This method, in which one side-band and a portion of the other are intentionally transmitted, is called Vestigial Side-Band Transmission.

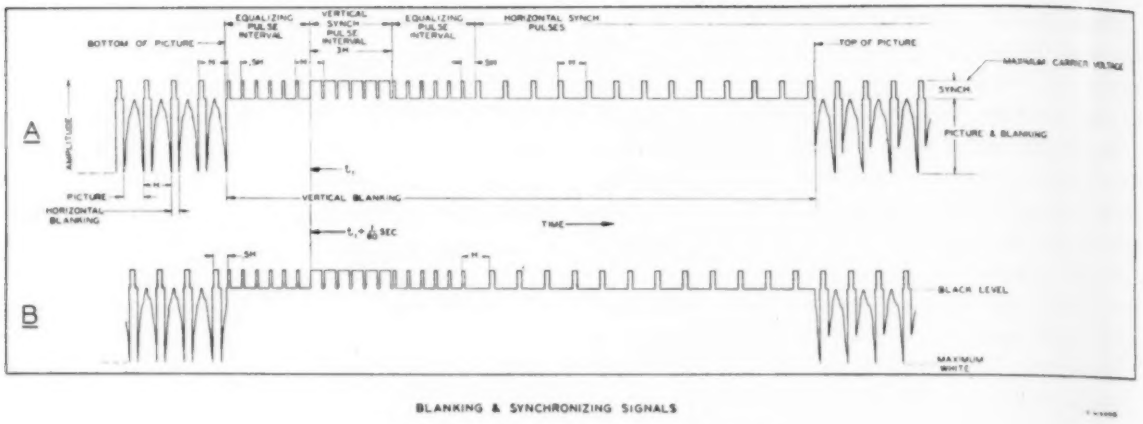


FIG. 6. Blanking and synchronizing signals.

second detectors. Separate automatic volume controls maintain the proper signal levels at the two detectors. The automatic volume control for sound operates on the average carrier level in the normal manner. The automatic volume control for picture, however, operates on the peak signal. This is necessary since "d.c. transmission" is used in which the average value of the transmitted signal must vary as a function of the total brightness of the picture being transmitted. This is illustrated in Fig. 4 where *A* represents the conditions for a predominantly white picture, while *B* is for a predominantly black picture. The peak value of the carrier representing synchronizing pulse peaks is maintained constant and may therefore be used as a reference for automatic volume control.

The picture intermediate frequency signal is rectified to a video signal and is amplified through the video frequency amplifier to a level sufficient to control the reproducing system. This amplifier must be so designed that it will pass the full video frequency band of approximately 60 cycles to 4,000,000 cycles with tolerable amplitude and phase distortion. In order to simplify the construction of this amplifier it may be made to pass only the a.c. component of the video signal, and the d.c. component, lost in this amplifier, may be restored in the final stage as illustrated in Fig. 5. The diode action of the grid circuit develops a bias which is proportional to the height of the synchronizing pulse peaks above the a.c. axis, which in turn is a function of the average brightness of the picture (the d.c. component).

The television signal contains specially shaped pulses for synchronizing at the end of each line and at the end of each field as illustrated in Fig. 6. This television signal, taken from the amplifier chain at a point where the amplitude and polarity are suitable, is impressed on synchronizing pulse separating circuits. The synchronizing pulses are derived from the television signal by passing it through an amplitude limiting amplifier, which passes the pulses and rejects the remainder of the signal. One method of accomplishing this is illustrated in Fig. 7. The output signal of the synchronizing separator is impressed on two circuits, one of which "integrates" it to derive the vertical (field) synchronizing pulse, as illustrated in Fig. 8; the other "differentiates" it to derive horizontal (line) synchronizing pulses, as illustrated in Fig. 9. These synchronizing signals are then impressed on the reproducing arrangement in the proper amplitude and polarity to synchronize the

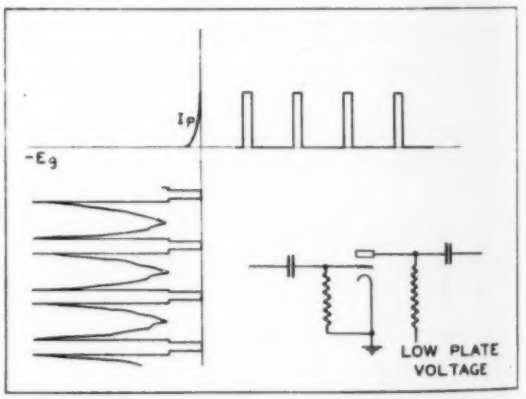


FIG. 7. Operation of synchronizing separator.

image reconstruction with the scanning at the transmitter.

Cathode-Ray Tube Television Reproduction

The arrangements for interception and amplification of the radio signal and for derivation of the original video and synchronizing signals from the radio signal are nearly the same in the cathode-ray and electro-mechano-optical systems. The reconstructing arrangements as well as the synchronizing means of the two systems are, however, radically different. In the cathode-ray television receiving system the image of the original scene is reconstructed on the luminescent screen of a cathode-ray tube. For synchronization, the electrical sawtooth waveshape generators, which control the deflection of the electron beam, are timed by the incoming synchronizing signals.

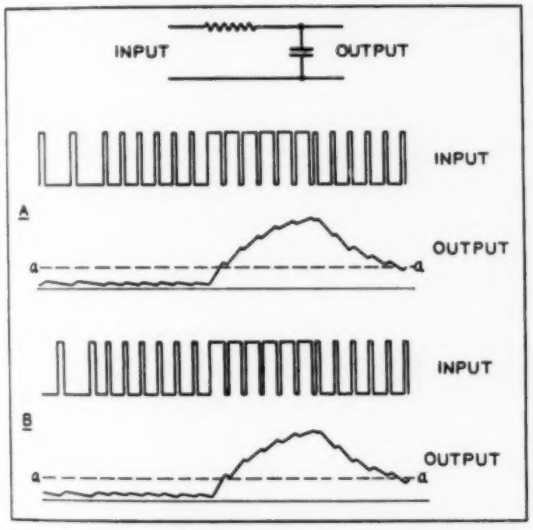


FIG. 8. Vertical selecting circuit.

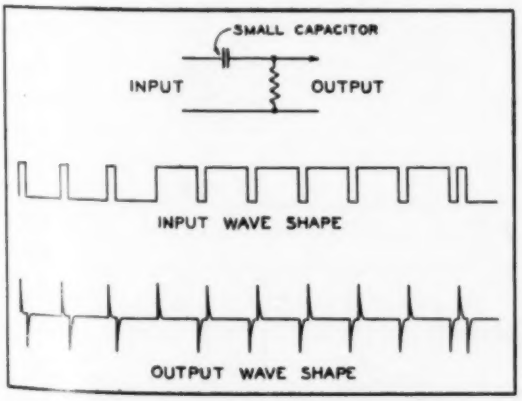


FIG. 9. Horizontal pulse selecting circuit.

FIG. 10. Cathode-ray tube for television receiver.

A photograph of a typical television cathode-ray tube is shown in Fig. 10. The tube shown in this photograph has a luminescent screen 12 inches in diameter and reproduces pictures in shades of black and white. Cathode-ray tubes for direct viewing have usually been made with glass envelope diameters at the screen end of 5, 9 or 12 inches. Larger tubes have been used experimentally but their size entails some manufacturing difficulties and makes the tubes cumbersome to handle.

A television cathode-ray tube is quite similar in its general construction to the familiar tube used in cathode-ray oscillographs. It consists essentially of four component parts: first, a glass envelope sealed for maintenance of high vacuum; second, an electron gun for emitting, controlling and focusing the electron beam; third, an arrangement (either internal or external) for deflecting the beam; and fourth, a luminescent screen on which the image is reproduced. A cross section of a typical television cathode-ray tube is shown in Fig. 11. The envelope is made of glass and is able to withstand the atmospheric pressure with a large margin of safety. The tube in its

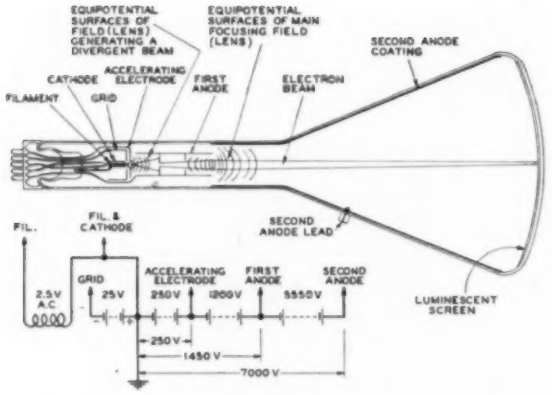


FIG. 11. Diagram of television cathode-ray tube.

processing is baked and evacuated to about 10^{-6} mm of mercury. The electron source is the cathode which is an indirectly heated metal cylinder with a barium strontium oxide-coated disk-shaped cap. The video signal is applied to a control electrode in the form of a cylinder concentric with and surrounding the cathode and having an apertured end. The voltage applied to this control electrode determines the number of electrons which pass through the aperture into first anode cylinder and finally to the screen. The first anode cylinder contains one or more apertured disks which serve to mask off some electrons whose initial emission velocities are such as would preclude their reaching a small area or spot on the screen. Some tubes employ an accelerating electrode between the control electrode and the first anode. The glass envelope of the tube (particularly the neck portion) carries a black conductive coating on its inner surface which is operated at a high positive voltage applied by means of a sealed-in terminal. This charged coating, comprising the second anode, accelerates the electrons and cooperates with the first anode to create an axially symmetrical electrostatic field (or electron lens) which starts the initially divergent electrons toward the axis of symmetry. By adjusting the ratio of the voltages of the first and second anodes to a suitable value depending upon the tube dimensions, the diameter of the luminous spot on the screen may be reduced to a minimum or optimum size. The voltage on the first anode is usually about one-fourth or one-fifth of that on the second anode.

A magnetostatic system may be used instead of an electrostatic system for focusing the beam. A magnetostatic field coaxial with an electron

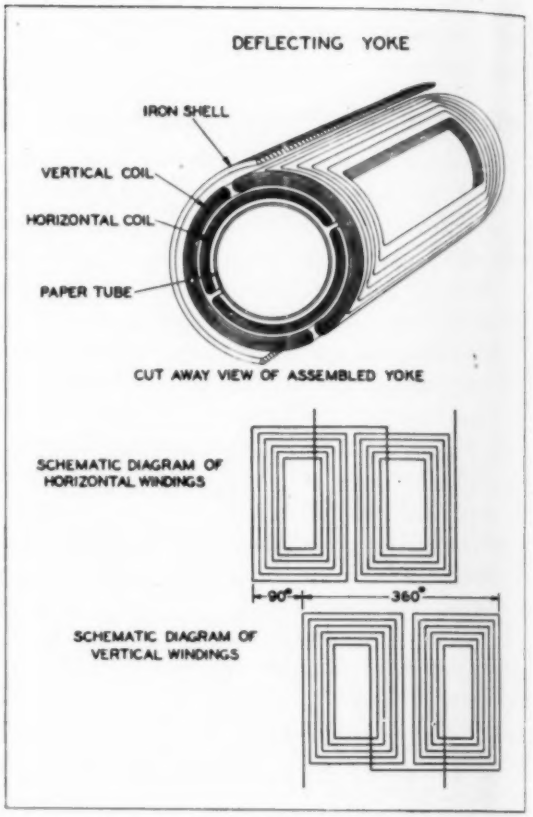


FIG. 12. Magnetic deflecting yoke.

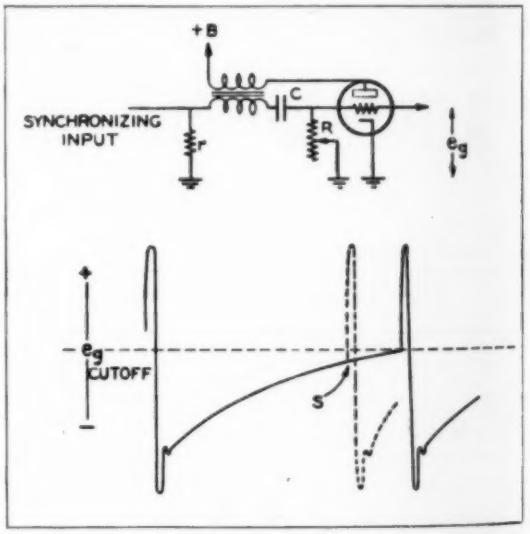


FIG. 13. Blocking oscillator.

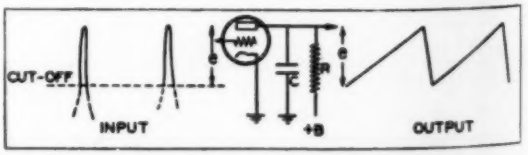


FIG. 14. Discharge tube circuit.

beam acts upon it similarly to an electrostatic field. The coils for producing this focusing magnetic field are placed on the outside of the tube.

Just as soon as the beam leaves the main focusing field (lens) it is subjected to the action of either magnetic or electric fields for the purpose of variably deflecting it in a predetermined manner as required for scanning. Vertical and horizontal scanning may be produced by three different combinations: first, by means of two electric fields at right angles to each other; second, with two magnetic fields at right angles to each other; and third, with electric and magnetic fields parallel to each other. For economy, magnetic deflection will generally be preferable for higher anode voltages. This is because the deflecting field strength required is proportional to the anode voltage for electrostatic deflection while it is proportional to the square root of the anode voltage for magnetic deflection. The tube of Fig. 11 requires all-magnetic deflection with the deflecting coils assembled in a yoke about the tube neck over the second anode coating. A deflecting yoke for magnetic deflection is shown in diagrammatic form in Fig. 12.

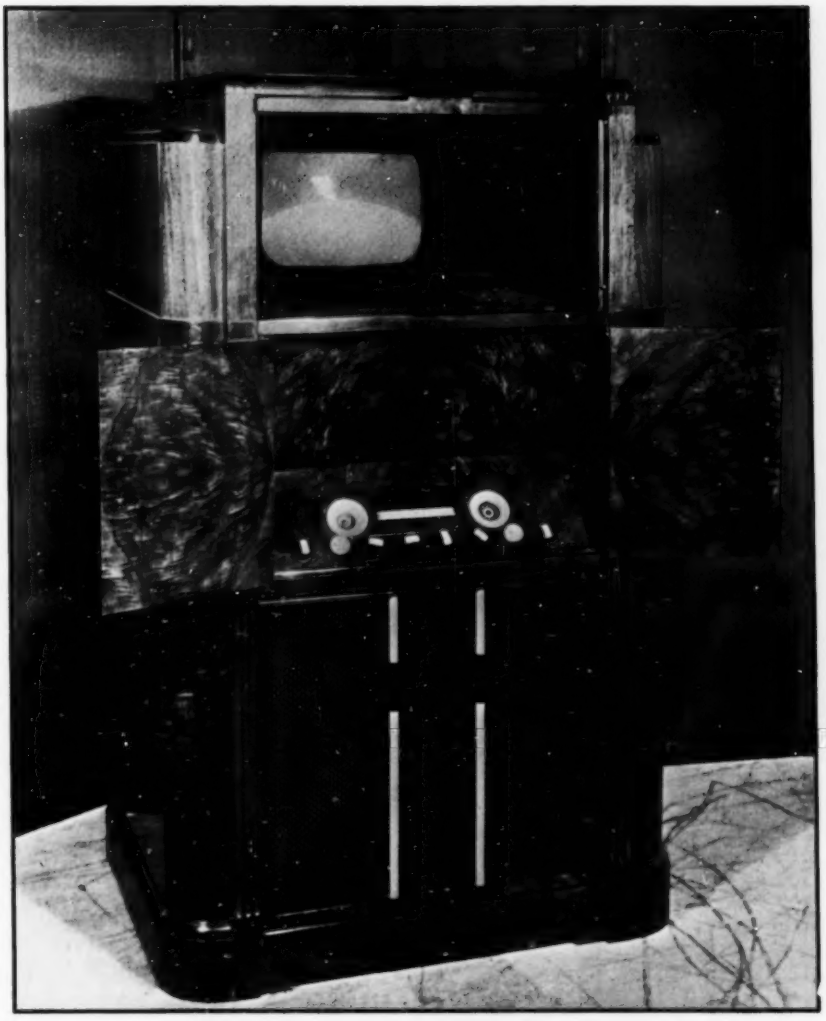


FIG. 15. Experimental type of television receiver.

The luminescent screen is placed on the inner side of the front face of the tube. This face is as flat as the mechanical strength of the glass permits. The phosphors which are usually either sulfides or silicates of zinc are deposited in a thin translucent layer. Some of the electrons originally drawn from the cathode are intercepted by the masking aperture disk of the first anode. They return to the source of the e.m.f. through the first anode lead. The remainder of the electrons strike the screen phosphor. They excite the phosphor and dissipate most of their kinetic energy there. Some of the energy of the beam striking the screen is transformed into light energy, some is transformed into heat, while the remainder is imparted to secondary electrons which are emitted from the screen. The secondary electrons move with low velocity and flow to the conductive coating forming the second anode. An equilibrium voltage condition is quickly established with the phosphor a few volts below the potential of the second anode coating. The difference of potential between the phosphor and

the second anode coating adjusts itself so that the latter draws the secondaries at the same rate as the rate of arrival of the primaries at the phosphor.

In a television cathode-ray tube used with 441-line, 30 frame/sec. interlaced transmission the beam is deflected horizontally 13,230 times per second and vertically 60 times per second. This is accomplished by means of sawtooth currents through deflecting coils in the case of magnetic deflection and by means of sawtooth voltages on deflecting plates in the case of electrostatic deflection. The synchronizing signals derived from the incoming television signal are applied to two generators of pulses, one for vertical and one for horizontal deflection. These generators (blocking oscillator type) produce large voltage pulses in synchronism with the incoming signals—see Fig. 13. These large voltage pulses are passed through tube circuits changing them into sawtooth voltages—see Fig. 14. Then, in the case of magnetic deflection, the sawtooth voltages are changed into sawtooth currents by amplifier tubes and sent through the deflecting coils. In the case of electrostatic deflection the sawtooth voltages are amplified and applied directly to deflecting plates inside the cathode-ray tube. Both the horizontal and the vertical deflecting circuits perform essentially the same functions, but the circuit arrangements and constants differ because of the wide difference in operating frequency.

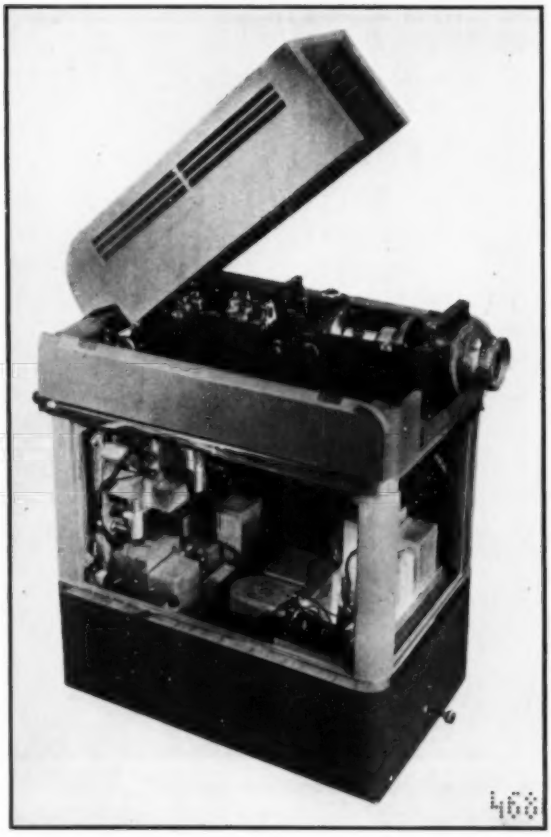


FIG. 16. Television receiver for producing large screen images by projection.

The video signal after suitable amplification is applied in proper polarity to the control (grid) electrode of the cathode-ray tube, while the "restored" d.c. component controls the average d.c. bias on the same grid.

Figure 15 shows a view of a television receiver that has been used in experimental field tests. A cathode-ray television receiver may be either of a direct viewing type such as is shown in Fig. 15, or of a projection type such as is shown in Fig. 16. In the former case, the image is viewed either directly on the screen of the cathode-ray tube or through a mirror while in the latter case it is viewed on a projection screen after an optical magnification of the image.

Projection television systems are subject to certain stringent requirements because of the large projected image and because much of the original light is lost in the process of projection. Reasonable light optics indicate luminescent screens that are relatively small, seldom over 5 inches in diameter. Electron beam current densities are high and approach saturation of the screen phosphor. Second anode voltages are high, that is, over 20,000 volts with some experimenters using voltages in the order of 50,000 to 70,000 volts.

Electro-Mechano-Optical Television Reproduction

Many mechano-optical systems, employing various combinations of rotating perforated disks (Nipkow disks), lens disks, drums, rocking mirrors, rotating prisms, mirror wheels and light modulating devices, have been used experimentally for television reception. Most of these have been eliminated for practical television with the advent of the use of the greatly increased

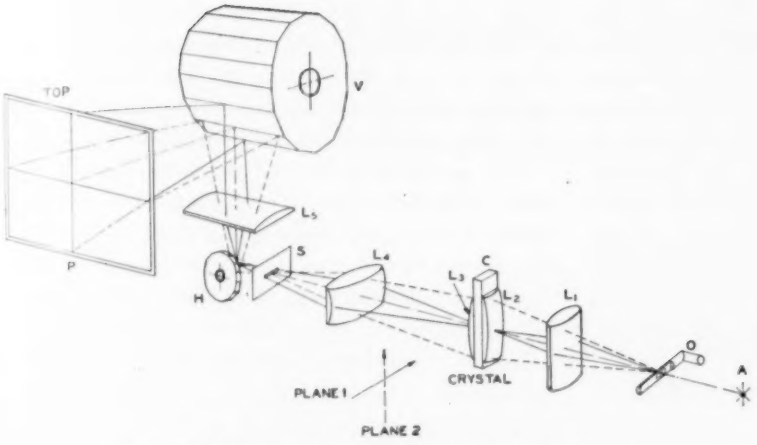


FIG. 17. Diagram of Scophony reproducing system.

number of lines in the picture required for high definition. Generally, in systems of this type, the useful light obtainable varies inversely as the square of the number of lines, since the used area of the light source must have a size proportional to a single picture elemental area. Still further decreases in brightness result from the necessity for reducing the sizes of the moving mirrors, lenses, etc., in order to allow them to be manipulated. One electro-mechano-optical system of television reception capable of producing pictures with reasonable resolution and brightness has recently been described—Scophony.[1] It employs a high pressure mercury arc as a light source and for light modulating means it makes use of a unique optical system.

Figure 17 shows the optical and scanning system in schematic form. Fig. 18 shows the optical system separately for the two planes so that its "split focus" feature, that is, the different focus points in the two planes, may be observed. (For simplicity in Fig. 18, mirrors on the vertical scanning mirror wheel V and on the horizontal scanning wheel H are shown as though they transmitted instead of reflected the light. Different directions of transmission for adjacent mirrors on each wheel are shown so that the scanning action is indicated.)

The lamp provides intense light which falls upon lens L_1 by passing above and below the obstacle or shield O. In plane 2, the obstacle O is imaged upon the slot S as a shadow or dark image by lenses L_1, L_2, L_3 and L_4. Since the image of the obstacle fills the slot, no light is transmitted beyond the slot when the piezoelectric crystal is not exciting the supersonic light modulating cell C. In plane 2, parallel light passes through the cell C and the cell is imaged upon the picture screen P. This results in a line of light extending from left to right on the screen.

In plane 1, the longer dimensions of the slit and of the obstacle are seen. In this plane the obstacle is apparently imaged upon the cell; then this cell, rather than the slit, is imaged as a line upon the screen. The light must be confined to the dimension of one picture element on the screen in plane 1.

As one mirror of the mirror wheel H causes a portion of the line image of the cell on the screen to miss the screen on the right, the next mirror replaces it on the screen at the left-hand side for the next scanning line. The horizontal scanning mirror wheel is required to run at about 40,000 r.p.m. (depending upon the number of mirror faces) for the reproduction of television transmissions in accordance with U. S. standards. The vertical deflecting mirror wheel must at the same time rotate at a speed of "60 mirror faces" per second.

The supersonic light modulating cell C is a transparent container filled with a suitable liquid

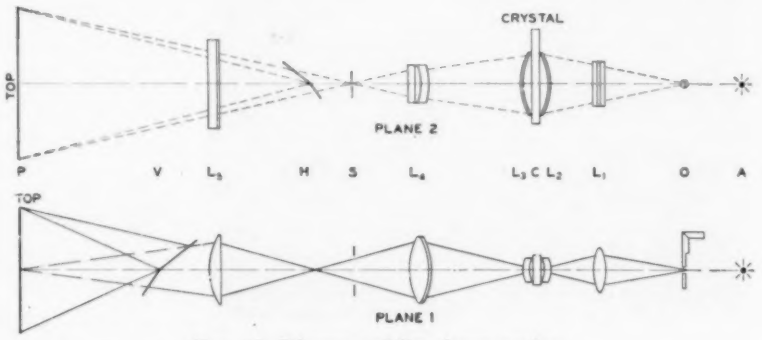


FIG. 18. Diagram of Scophony optics.

[1] H. S. Lee, "The Scophony Television Receiver," Nature **142**, 59 (1938).

adapted to be mechanically excited (at the bottom end in Fig. 17) by an oscillating quartz crystal. The crystal is driven by a 10-megacycle carrier signal which is modulated in amplitude by the video signal. The upper end of the cell is terminated in an energy-absorbing or damping device. The crystal produces mechanical waves of alternate compression and rarefaction in the liquid which have a wave-length of the order of 0.01 cm and which are propagated at a velocity of about 100,000 cm per second along the cell and into the damping device.

The obstacle *O*, imaged upon the slit, allows no light to pass the slit when the cell is not excited. In this condition the cell acts as a plane transparent glass plate. When any portion of the cell is active due to the applied signal waves, that particular region of the cell suffers a change in its index of refraction in periodic strips, which causes diffraction of the light passing through the cell. The effect is similar to that which would occur if the internal mechanical strains were mechanical corrugations in the surface instead. The net effect is that the light from the excited areas of the cell is deflected from its previous path. This allows light which passes above or below the obstacle *O* to pass through the slit *S* in accordance with the magnitude of the excitation. The light through each portion of the cell is thereby modulated by the video wave as it is propagated in the fluid.

The scanning action of the mirror wheel *H* is such as to move the line image of the cell on the screen along itself toward the right-hand side of the received picture. By suitable design the velocity of propagation of the signal wave in the cell is made equal to the horizontal scanning velocity at the screen when allowance is made for the optical enlargement of the cell image on the screen. This results in each portion of the image of the cell on the screen having instantaneous brightness in accordance with the brightness of the corresponding portion of the transmitted picture.

Acknowledgment

Acknowledgment is here given for the generous assistance of Messrs. A. V. Bedford, R. S. Holmes and I. G. Maloff in the preparation of this review.

Electron Optics

BY E. G. RAMBERG AND G. A. MORTON

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1. Introduction

A SURVEY of the literature on electron optics available at the present time[1] makes it difficult to realize that this field did not exist even in name thirteen years ago. The reason for its rapid development in this brief period rests primarily on two circumstances: first, the strongly felt need for a unifying point of view in the treatment of the motion of electrons in electric and magnetic fields, utilized in an ever increasing number of electronic devices—particularly in the field of television—and, second, the development of new devices suggested by this new, optical approach, exemplified by the electron microscope.

Electron optics—more accurately called geometric electron optics—concerns itself with the paths of electrons in electric and magnetic fields in much the same manner as geometric light optics is concerned with the paths of light rays through systems of lenses and prisms or media of variable index such as our atmosphere. The close analogy existing between the laws governing light rays and paths of material particles such as electrons was first recognized by W. R. Hamilton a hundred years ago. Just as Fermat's theorem or the law of least time

$$\delta\int_a^b n\,ds=0 \tag{1}$$

determines the path taken by a light ray between the points a and b, so the law of least action in the form

$$\delta\int_a^b p\,ds=0 \tag{2}$$

determines the path of a particle traveling from a to b, provided that the force acting on it can be expressed as the gradient of its potential energy as is the case for a charged particle in a purely electric field. n and p are the index of refraction and the momentum of the particle, respectively, considered in either case as functions of position. In the presence of a magnetic field a similar variation theorem applies, in the form

$$\delta\int_a^b \{p-eA\cos\chi\}ds=0, \tag{3}$$

where e is the absolute value of the electronic charge, A the magnitude of the vector potential of the magnetic field ($H=\text{curl } A$) and χ is the angle between the direction of A and that of the path of the electron. The important point is that, in either case, an "electron index of refraction" proportional to the momentum of the electron p or the more complex integrand in Eq. (3), e.g.

$$\begin{aligned} n&=\left\{\frac{p}{mc}-\frac{eA}{mc}\cos\chi\right\}\\ &=\frac{\beta}{(1-\beta^2)^{\frac{1}{2}}}-\frac{eA}{mc}\cos\chi\\ &=\left(\frac{2e}{mc^2}\right)^{\frac{1}{2}}\left\{\left(\varphi+\frac{e\varphi^2}{2mc^2}\right)^{\frac{1}{2}}-\left(\frac{e}{2m}\right)^{\frac{1}{2}}A\cos\chi\right\} \end{aligned} \tag{4}$$

FIG. 1. Electrolytic tank.

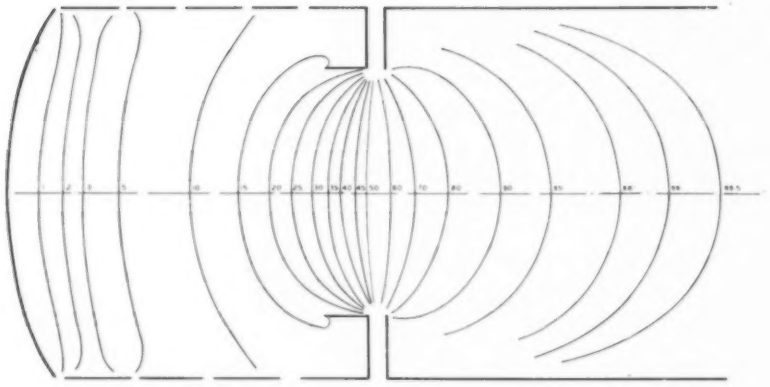


FIG. 2. Potential map of an image tube.

can be defined. Here β is the ratio of the electron velocity v to the velocity of light c and φ is the electric potential with the zero fixed so that

$$E_{\text{kin}}=e\varphi. \tag{5}$$

It is seen that for a purely electric field and potentials below 20 kv the index is given, but for an arbitrary multiplying constant, by the square root of the electric potential.* It is purely a function of position, just as the index of refraction of any isotropic optical medium is a function of position only. In the presence of a magnetic field the electron index depends on the direction of motion of the electron as well, so that, as in the case of crystal optics, the medium is anisotropic.

The analogy can be carried even further. Both Fermat's law, Eq. (1), and the principle of Lagrange, Eqs. (2) and (3), may be derived from wave optics and wave mechanics, respectively, for the limiting case where the variation in index is negligible within the range of a wavelength. The wave-length for light is given by the usual relation $(c/v)/n$, v being the frequency of the light wave. The wave aspect of matter was predicted by L. de Broglie[2] and confirmed experimentally by Davisson and Germer.[3] The expression giving the wave-length of material particles is h/p, where h is Planck's constant. In the case of electrons this expression becomes:

$$\lambda=12.34/(\varphi+0.98\cdot10^{-6}\varphi^2)^{\frac{1}{2}}, \tag{6}$$

where φ is the potential in volts and λ the wavelength in angstrom units. This wave mechanics approach to electron optics is important because it makes it possible to estimate the limits placed on the resolving power of electron-optical instruments by diffraction on the same basis as for ordinary optical instruments. Thus for the electron microscope, as for the light microscope, the least resolvable separation is

$$d=\lambda/(2\sin\theta), \tag{7}$$

where θ is the aperture angle of the imaging beam at the object. Full use, it is true, cannot be made at the present time of the smallness of λ in this relation, owing to inability to adequately overcome certain image defects to be discussed later on.

In spite of the close analogy between electron and light rays, there are certain important differences. Those which are of greatest interest from the standpoint of electron optics are the following.

(1) The energy of an electron beam may be increased arbitrarily by acceleration through an electric field, while that of a light beam is fixed except for eventual losses by partial reflection, absorption and scattering.

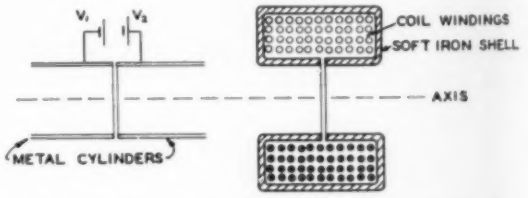


FIG. 3. Electric and magnetic lenses with identical field distributions.

(2) Electron beams cannot be polarized.*

(3) The media of electron optics have continuously variable index while those normally utilized in light optics are media of constant index bounded by surfaces at which the index changes abruptly.

(4) The refracting fields of electron optics (in

* At 20 kv the error in the index due to this approximation is only one percent.

* While the individual electron is known to be polarized due to its spin, it has not been found possible so far to orient and separate according to their spin free electrons.

vacuum) are subject to Laplace's equation, placing definite restrictions on the optical perfection of the image, while the shapes of the refracting surfaces of light optics are arbitrary.

(5) The refractive power of electron-optical elements can be changed by simply changing the potentials of electrodes and the currents in coils while that of light-optical elements is, in general, fixed.

(6) The range of the electron-optical index of refraction, being for low potentials proportional to the velocity of the electron, is practically unlimited, while light indices vary by no more than, approximately, 2 : 1.

(7) Unlike light rays, electron rays affect each other due to the mutual repulsion of the electrons, giving rise to space charge effects.

The third and fourth differences are primarily responsible for the fact that, although the theory of geometrical light optics may be applied *in toto* to electron optics, the practical methods of optical design differ considerably in the two cases. In the case of light optics the refracting surfaces between media of different given indices can be formed directly, while only the electrodes and coils producing the refracting fields of electron optics can be shaped, not the fields themselves. In general, in electron optics it is not possible to assume an electron path and from it to determine the electrode or coil configuration producing this motion because of the mathematical complexity involved. The practical procedure is instead to determine the fields from assumed electrodes or coils, and to trace the electron paths through these fields. If the path does not coincide with that required, the field producing

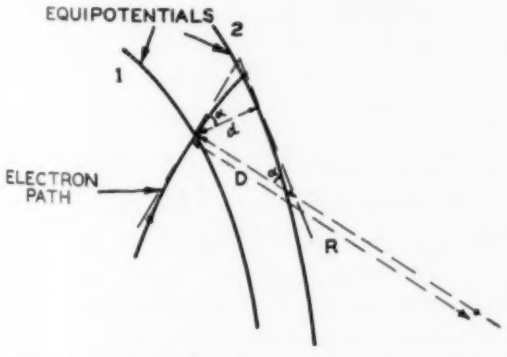


FIG. 4. Graphical determination of electron paths in electric field.

elements are altered and the determination repeated.

2. *Determination of Refractive Fields*

In electron optics the fields of primary interest are those produced by systems of plane symmetry—i.e., configurations symmetrical about any plane parallel to the xy plane and thus independent of z—and systems of axial symmetry, made up of coaxial cylindrical elements. In light optics the first correspond to prisms and

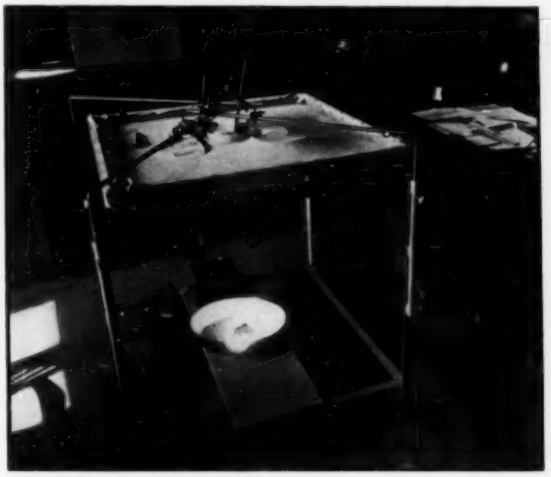


FIG. 5. Rubber model for determining electron paths.

cylinder lenses, the second to rotationally symmetric or ordinary, spherical lenses. To begin with, purely electric refracting fields will be considered.

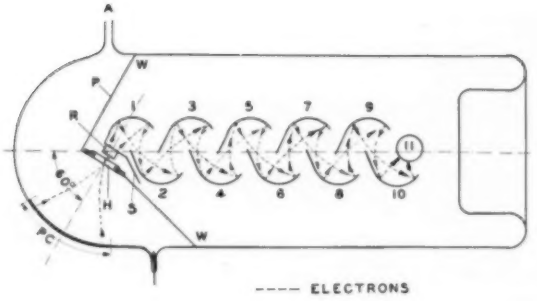
Unfortunately the analytical solution of Laplace's equation determining the fields in the absence of appreciable space charge for these two cases, i.e.,

$$\partial^2\varphi/\partial x^2+\partial^2\varphi/\partial y^2=0 \tag{8a}$$

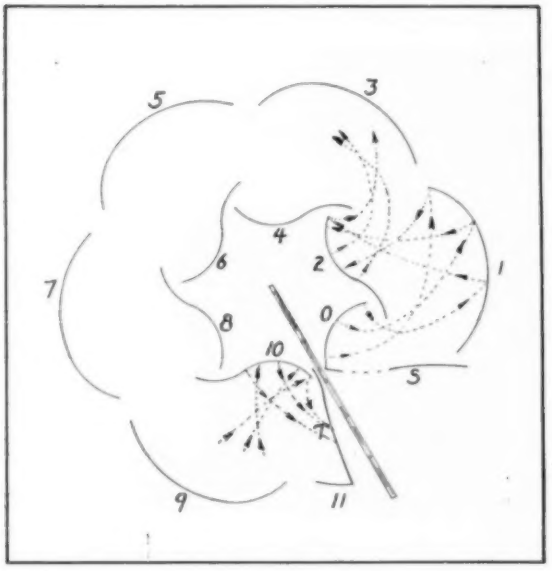
and

$$\frac{1}{r}\frac{\partial}{\partial r}r\frac{\partial\varphi}{\partial r}+\frac{\partial^2\varphi}{\partial z^2}=0 \tag{8b}$$

is possible only for the very simplest boundary conditions. There is, however, a very general way of determining potential distributions, applicable in either case. This is the method of the electrolytic tank.[4] An enlarged model of the electrode configuration is immersed in a tank containing an electrolyte—e.g. ordinary tap



(a)



(b)

FIG. 6. Electrode structures of secondary emission multipliers. (a) Linear type, (b) circular type.

water—in such a way that the surface of the electrolyte just coincides with a plane of symmetry of the electrode configuration. As potentials are applied to the electrodes, ohmic space currents will flow in the electrolyte, obeying the law

$$j=\sigma E, \tag{9}$$

where j is the current density, σ the (constant) conductivity of the electrolyte and E the electric field. As the charge distribution in the electrolyte remains constant the current obeys the continuity equation

$$\text{div } j=0, \tag{10}$$

which, since $E=-\text{grad } \varphi$, is equivalent to Laplace's equation

$$\text{div grad } \varphi=\nabla^2\varphi=0.$$

Thus the potential distribution between the electrodes in the electrolytic tank is the same as though the electrodes had been placed in a vacuum.

Thus, if a probe at fixed potential, attached to one arm of a pantograph, is immersed in the liquid and made to follow a path along which the current to the probe vanishes, the other arm will trace out directly the equipotential corresponding to the potential of the probe. Fig. 1 shows an electrolytic tank arranged for this purpose with slide wire potentiometers for adjusting the potentials of the electrodes of the model on the side of the stand. Fig. 2 shows, as example, the plot obtained for an electrostatic image tube in this manner, placing successively different potentials on the probe. In practice alternating voltages of, e.g., 400 cycles per second, are applied to the electrodes and the probe to avoid polarization effects.[5]

This method may also be applied to the determination of the magnetic field distribution produced by a high permeability iron enclosed coil with a gap, provided that the iron is not saturated anywhere. To a sufficient approximation the surfaces of the two poles of the gap may then be regarded as magnetic equipotentials, $\psi=\text{const.}$, where

$$H=-\text{grad } \psi \tag{11}$$

and the magnetic field distribution between them will be identical with the electrical field distribution between two electrodes of similar shape (Fig. 3).

In more general cases the magnetic field distribution must be measured ballistically with the aid of exploring coils, by the Hall effect[6] or making use of the change in resistance in a magnetic field of some metals such as bismuth.[7]

3. *Graphical and Mechanical Electron Path Determination*

In the case of purely electric fields, the electron trajectories can be readily determined graphically from an equipotential map obtained as described above. Referring to Fig. 4 for a definition of the several symbols, the basic equation for the radius of curvature R of the

path at any point can be written as

$$mv^2/R = eE_r; \quad R = 2\varphi/E_r = 2\varphi d/(\Delta\varphi \sin\alpha) = D(\varphi_2+\varphi_1)/(\varphi_2-\varphi_1), \quad (12)$$

where E_r is the field component normal to the path. By it the center of curvature is determined and the path to the next equipotential approximated by a circular arc. At the next equipotential a new center of curvature is found and the process repeated so that the resulting approximation to the true path consists of a series of circular arcs joined smoothly together.

Ingenious devices for carrying out this path plotting mechanically in conjunction with the electrolytic tank have been designed and built by D. B. Langmuir[8] and D. Gabor.[9] Here the field measured between two closely adjoining probes placed along a line which is kept normal to the motion of the probe assembly, as well as the magnitude of the potential, measured by the same probes, control the direction of motion of the recording carriage on one arm of the pantograph as well as that of the probe assembly on the other.

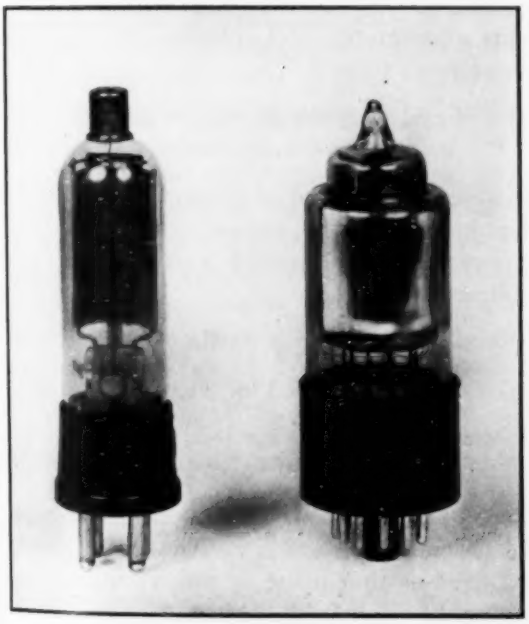


FIG. 7. Experimental secondary emission multiplier and photo-tube.

For "plane" electrode configurations there exists a simple shortcut to the determination of the electron paths. A model of the electrodes under consideration is constructed in such a way that the height of each element is proportional to the difference between its potential and that of the most positive electrode. Over this model is stretched a rubber membrane which is constrained to be in contact with the tops of the electrode models. The height of the membrane at any point will then be proportional to the potential at corresponding points within the actual electrode configuration. Furthermore, the horizontal projection of the motion of a steel ball moving under the influence of gravitation on this rubber membrane is exactly similar to that of an electron in the field between the electrodes. These statements assume (1) that the additional stretching of the membrane as the result of placing it on the model is small; (2) that the slopes of the membrane are small throughout; (3) that the curvature of the membrane is small compared to that of the ball; and (4) that the effect of friction in reducing the energy of the ball is negligible. These conditions can be fulfilled in practical cases to a sufficient degree to make this "rubber model" method a very valuable tool. Fig. 5 shows a rubber model set up for determining electron paths in a secondary emission multiplier.[10] The paths of the rolling balls may be photographed directly if the model is illuminated with a powerful light source. If the latter is intermittent it is possible at the same time to determine the velocity of the electron at any point from the separation of the "dashes" which make up the photographed path.[11]

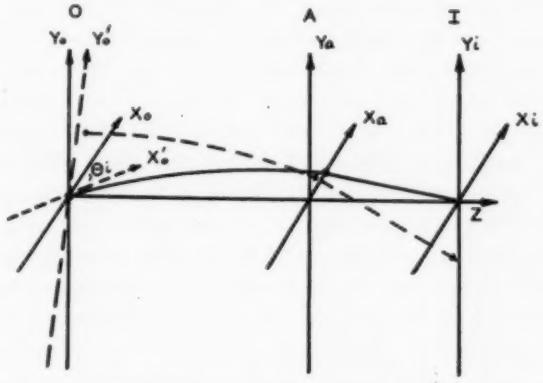


FIG. 8. Object, aperture and image planes of an electron-optical system.

The electron optics of "plane" systems finds

rather wide application. A development that has been guided throughout by this phase of electron optics and been benefited particularly by the rubber model is that of the electrostatic secondary emission multiplier.[10] Here the primary problem is to guide all the secondary electrons emitted by one target to the next, where they are to emit a larger number of secondaries. Fig. 6 illustrates some electrode structures that have proved satisfactory, while in Fig. 7 an experimental 8-stage photosensitive multiplier having a gain of 1,000,000 is shown in comparison with an ordinary photo-tube. Another simpler example are the deflecting plates in a cathode-ray tube. Finally, in amplifier tube design the distribution of current over the electrodes may be found by electron path determinations.[12, 13] This has led, as in the case of beam power tubes, to a reduction in undesirable grid currents. Wherever space charge plays a role the problem is, it is true, greatly complicated due to the greater difficulty of determining the potential, which now must satisfy Poisson's equation

$$\Delta\varphi = -4\pi\rho. \tag{12}$$

For the plane case the variation principle Eq. (2) leads to the differential equation for the path

$$\frac{d^2y}{dx^2} = \frac{1}{2\varphi}\left(\frac{\partial\varphi}{\partial y} - \frac{dy}{dx}\frac{\partial\varphi}{\partial x}\right)\left(1+\left(\frac{dy}{dx}\right)^2\right), \tag{13}$$

which may, of course, also be obtained directly from the equations of motion of the electron.

4. *First-Order Imaging by Axially Symmetric System*

It is the axially symmetric case, however, which brings out most clearly the similarity of light and electron optics. H. Busch,[14] in one of his fundamental papers, was, indeed, able to show that *any* axially symmetric electric and magnetic field would, to a first approximation, form a geometrically faithful, sharp image—corresponding to the "Gaussian" image of ordinary optics. Here this will be shown in a somewhat different manner for the important case that the image plane I is located in field-free space beyond the focusing fields (Fig. 8). The aperture plane A is defined as some plane between the object plane O and the image plane I, close enough to be, also, in field-free space. Then, considering electrons leaving the object plane throughout with the same velocity, though generally in different directions, it may be stated that, in general, any electron path between O and I is completely determined if two of its points are known, e.g. its intersections with the object and aperture planes. Hence, also, the

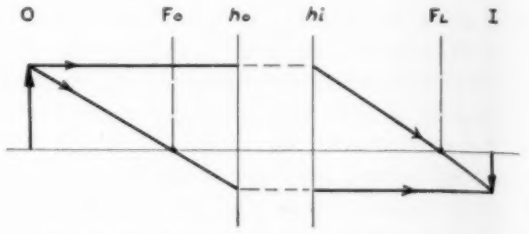


FIG. 9. Focal points and principal planes of an optical system.

coordinates of the intersection with the image plane, x_i, y_i, are determined by the coordinates of the intersections with the other two planes, x_0, y_0 and x_a, y_a, respectively, and they may be written, in view of the continuity of the force fields guaranteed by Laplace's equation, as a power series thereof. Thus

$$x_i = a_0 + a_1x_0 + a_2y_0 + a_3x_a + a_4y_a + a_5x_0^2 + a_6x_0y_0 + a_7y_0^2 + a_8x_0x_a. \tag{14}$$

Because of the axial symmetry this condition must hold even if the radius vectors to the three intersections are rotated through the same arbitrary angle θ:

$$x \to x\cos\theta - y\sin\theta; \quad y \to x\sin\theta + y\cos\theta. \tag{15}$$

Eq. (14) will be fulfilled for all values of θ only if

$$\begin{aligned} x_i &= a_1x_0 + a_2y_0 + a_3x_a + a_4y_a + 0(3), \\ y_i &= -a_2x_0 + a_1y_0 - a_4x_a + a_3y_a + 0(3), \end{aligned} \tag{16}$$

where $0(3)$ indicates terms of third and higher odd orders in x_0, y_0, x_a, y_a. The image plane is now fixed as that plane in which a specific ray, leaving the origin in the object plane and passing through $x_a = c$, $y_a = 0$, where c is very small, intersects the axis.* Then $a_3 = a_4 = 0$ and, to the

* In the case of a purely electric field the electron leaving the axis in the object plane proceeds throughout in the same meridional plane, as all the forces acting on the electron lie in this plane. In the presence of a magnetic field it may be shown that the angular velocity about the axis of an electron traversing it at any point must vanish in the field-free region beyond A, so that here, also, the path

first approximation

$$x_i = a_1 x_0 + a_2 y_0 = \beta x_0'; \quad y_i = -a_2 x_0 + a_1 y_0 = \beta y_0';$$

where

$$\begin{aligned} x_0' &= x_0 \cos\theta_i - y_0 \sin\theta_i; \\ y_0' &= x_0 \sin\theta_i + y_0 \cos\theta_i; \\ \theta_i &= \arctan(-a_2/a_1); \quad \beta = (a_1^2 + a_2^2)^{\frac{1}{2}}. \end{aligned} \tag{17}$$

Thus a geometrically similar image of the object, rotated with respect to the latter through an angle θ_i and magnified β times, is obtained. In the case of a purely electric field the angle θ_i is zero, while in the presence of a magnetic field the integration of the equations of motion yields

$$\theta = \left(\frac{e}{8m}\right)^{\frac{1}{2}} \int_{z_0}^{z} \frac{H}{\sqrt{\Phi}} dx, \tag{18}$$

where H and Φ are the magnetic field and electric potential along the axis, with $\theta = \theta_i$ for $z = z_i$.

5. *Determination of First-Order Image Properties of Electron Lenses*

The practical determination of the electron-optical properties of axially symmetrical systems follows along lines similar to those described for two-dimensional configurations. The field distribution must first be determined, either by measurement or calculation. Because of the nature of the path or "ray" equations for this type of system, only the potential and magnetic field strength (together with their derivatives) on the axis are necessary.

The path, or "ray" equation for first-order imaging in the form of a differential equation is

$$r'' + \Phi' r'/2\Phi + (\Phi''/4\Phi + eH^2/8m\Phi) r = 0, \tag{19}$$

where the radius vector to the electron is

$$re^{i\theta} = x + iy,$$

θ being given by Eq. (18).* The primes signify differentiation with respect to z. Eq. (19) may be obtained from the Euler equation† of the variation principle, Eq. (3), together with the expansions, valid for axially symmetric fields satisfying the Laplace equation:[16]

$$\varphi(r, z) = \sum_{\nu=0}^{\infty} (-1)^{\nu} \frac{\Phi^{(2\nu)}(z)}{(\nu!)^2} \left(\frac{r}{2}\right)^{2\nu}, \tag{20}$$

$$A(r, z) = \sum_{\nu=0}^{\infty} \frac{(-1)^{\nu} H^{(2\nu)}(z)}{\nu!(\nu+1)!} \left(\frac{r}{2}\right)^{2\nu+1}. \tag{21}$$

This equation makes it possible to determine completely the first-order properties of the image, i.e., its position, orientation and magnification, as well as the position of the focal points (F_0, F_i) and principal planes (h_0, h_i) of the electron lens system (Fig. 9).* Defining

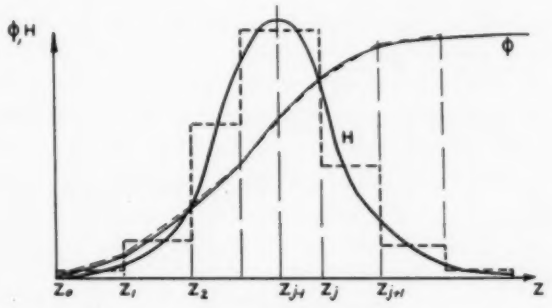


FIG. 10. Approximate representation of electric potential and magnetic field distribution.

$Oh_0 = u$, $h_i I = v$, $F_0 h_0 = f_0$ and $h_i F_i = f_i$, it can be shown that

$$\frac{(\Phi_0)^{\frac{1}{2}}}{u} + \frac{(\Phi_i)^{\frac{1}{2}}}{v} = \frac{(\Phi_i)^{\frac{1}{2}}}{f_i} = \frac{(\Phi_0)^{\frac{1}{2}}}{f_0} \tag{22}$$

finally becomes a straight line in a meridional plane, reference 15. Thus, in either case, the path must again intersect the axis in some real or virtual point (including infinity).

* r is real throughout and represents the numerical value of the distance of the electron from the axis for any electron starting in the xz plane (corresponding to $\theta = 0$) with an initial velocity vector lying in this plane. Quite generally it is the radius vector to the electron referred to a coordinate system rotated about the z axis through the angle $\theta(z)$ given by Eq. (18).

† The Euler equations of $\delta \int n ds = \delta \int F(r', \theta', r, \theta, z) dz = 0$, where, for the axially symmetric case,

$$F(r', \theta', r, \theta, z) = \left(\frac{2e}{mc^2}\right)^{\frac{1}{2}} \left\{ \left[\left(\varphi + \frac{e\varphi^2}{2mc^2}\right)(1 + r'^2 + r^2\theta'^2) \right]^{\frac{1}{2}} - \left(\frac{e}{2m}\right)^{\frac{1}{2}} A_\theta r\theta' \right\},$$

are

$$\frac{\partial F}{\partial r} - \frac{d}{dz}\frac{\partial F}{\partial r'} = 0; \quad \frac{\partial F}{\partial \theta} - \frac{d}{dz}\frac{\partial F}{\partial \theta'} = 0.$$

Eqs. (18) and (19) are obtained from them if the term $e\varphi^2/2mc^2$ is neglected, the expansions Eqs. (20) and (21) are substituted for φ and A_θ, respectively, and all terms involving powers of r and r' higher than the first are dropped.

* In an electron lens system, unlike the case of the ordinary optical thick lens shown, the principal planes are always crossed (reference 22), i.e., h_i lies between 0 and h_0.

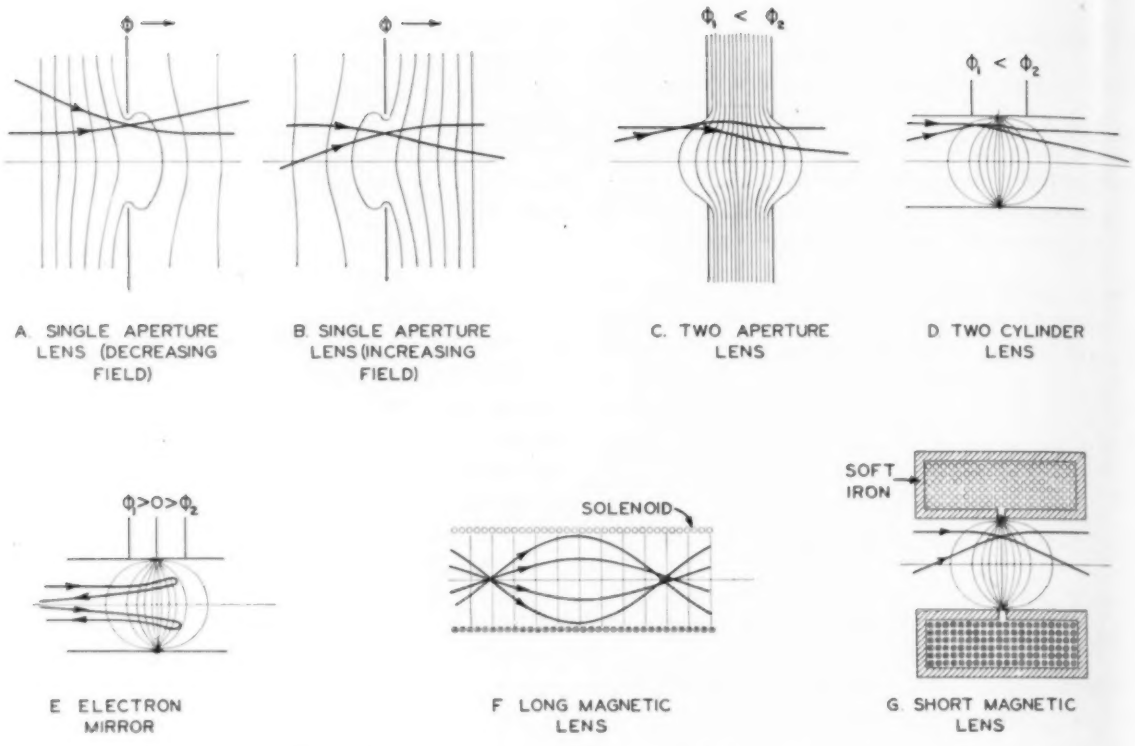


FIG. 11. Electron paths in various types of electron lenses.

and

$$m=(\Phi_0/\Phi_i)^{\frac{1}{2}}v/u, \tag{23}$$

where m is the magnification. These correspond exactly to the analogous expression in optics with $(\Phi)^{\frac{1}{2}}$ playing throughout the rôle of the refractive index.

As an example, it is possible to derive as expressions for the focal length of a thin electric and magnetic lens[17]

$$\frac{1}{f_i}=\frac{1}{4\Phi_i^{\frac{1}{2}}}\int_{-\infty}^{\infty}\frac{\Phi''}{\Phi^{\frac{1}{2}}}dx=\frac{1}{8\Phi_i^{\frac{1}{2}}}\int_{-\infty}^{\infty}\frac{\Phi'^2}{\Phi^{\frac{1}{2}}}dz, \tag{24a}$$

$$\frac{1}{f}=\frac{e}{8m\Phi}\int_{-\infty}^{\infty}H^2dz=\frac{0.022}{\Phi_{\text{volts}}}\int_{-\infty}^{\infty}H^2_{\text{gauss}}dz, \tag{24b}$$

respectively.

Equation (19) can be solved in a simple manner if the axial electric potential is approximated by a broken line and the axial magnetic field by a step function as shown in Fig. 10. In this case the solution between the points z_j and z_{j+1} becomes

$$r=r_j\cos 2\left(\left\{d\left(z-z_j+\frac{\Phi_j}{\Phi'}\right)\right\}^{\frac{1}{2}}-\left\{\frac{d\Phi_j}{\Phi'}\right\}^{\frac{1}{2}}\right)+\left\{\frac{\Phi_j}{\Phi' d}\right\}^{\frac{1}{2}}r_j'\sin 2\left(\left\{d\left(z-z_j+\frac{\Phi_j}{\Phi'}\right)\right\}^{\frac{1}{2}}-\left\{\frac{d\Phi_j}{\Phi'}\right\}^{\frac{1}{2}}\right) \tag{25a}$$

with $d=eH^2/(8m\phi')$, while the change in slope of the path at z_j is given by

$$r_{j+}'-r_{j-}'=\frac{r_j}{4\Phi_i}\{\Phi_-'-\Phi_+'\}. \tag{25b}$$

The approximate path obtained by this solution consists of a broken curve; for purely electric fields the individual curve elements are parts of parabolas,[18] for purely magnetic fields portions of a sine curve, as may be seen if it is assumed that $d\to 0$ and $\Phi'\to 0$, respectively.

Figure 11 shows the paths of electrons in the fields of a number of typical electron lenses. The first case, that of the aperture between two

regions of different field, was first treated by Davisson and Calbick,[19, 20] who gave for the focal length

$$f=4\Phi/(\Phi_b'-\Phi_a'). \qquad (26)$$

The lenses formed by two apertures or cylinders, respectively, at different potentials belong to the most important types of electric lenses used in practice, finding application in particular in electron guns, image tubes and emission microscopes. A possible use for the electron mirror may prove to be the correction of the chromatic aberration introduced by electron lenses, to be discussed below. A negatively biased control grid in a cathode-ray tube is a type of electron mirror frequently encountered. Finally, in the magnetic lenses the paths of the electrons in the meridional plane rotating with them, together with the magnetic equipotentials $\psi=$const., are shown.

6. *Aberrations in Electron Imaging*

In general it is not enough to know the position and magnification of the image produced by an optical system. The quality of the image is also of importance. This is determined by the image defects or aberrations. These are significant even where, as in the case of the spot produced by an electron gun, the size of the image alone is of interest, as they may exert an important influence on the latter.

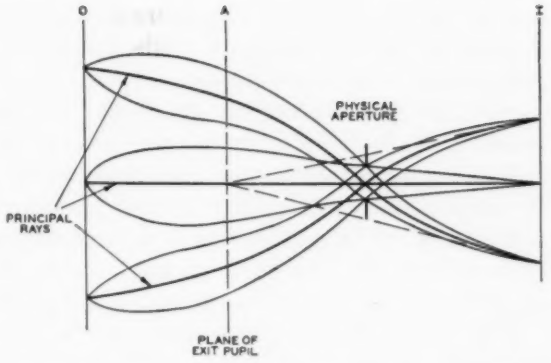


FIG. 12. Determination of the aperture plane as plane of the exit pupil.

Three kinds of image defects may be distinguished—geometric aberrations, chromatic defects and space charge defects. The first are encountered if objects of finite extent imaged by electron pencils of uniform velocity but finite aperture are considered—in other words, if the terms of third and higher power in Eq. (16) are included in the consideration. Confining attention to the terms of third order in the coordinates and making use of the fact that the electron rays must satisfy a variation principle such as Eq. (3), the deviation of the path intersection with the image plane from the first-order or Gaussian image point[15] becomes:

$$\begin{aligned}
\Delta x_i = &-\zeta x_a(x_a^2+y_a^2) && \text{Aperture Defect (Spherical Aberration)}\\
&-Re(\epsilon/2)\{x_0'(x_a^2+y_a^2)+2x_a(x_0'x_a-y_0'y_a)\} && \text{Coma}\\
&+Im(\epsilon/2)\{y_0'(x_a^2+y_a^2)-2x_a(x_0'y_a-y_0'x_a)\} && \text{Anisotropic Coma}\\
&-\beta x_a(x_0'^2+y_0'^2) && \text{Curvature of Field}\\
&-Re(\gamma)\{x_a(x_0'^2-y_0'^2)+2x_0'y_0'y_a\} && \text{Astigmatism}\\
&-Im(\gamma)\{y_a(x_0'^2-y_0'^2)-2x_0'y_0'x_a\} && \text{Anisotropic Astigmatism}\\
&-Re(\alpha)x_0'(x_0'^2+y_0'^2) && \text{Distortion}\\
&+Im(\alpha)y_0'(x_0'^2+y_0'^2). && \text{Anisotropic Distortion}
\end{aligned} \qquad (27)$$

The expression for Δy_i is obtained from the above by substituting y for x and $-x$ for y. These expressions are thus polynomials in x_a, y_a, x_0' and y_0' containing eight coefficients which depend on the axial fields and potentials of the imaging systems as well as on the choice of the object and aperture planes; the symbols used for these coefficients are those of Scherzer, who has tabulated them in terms of the axial fields and potentials and the first-order rays in a form best adapted for calculation.[21] *Re* signifies "real part" and *Im* "imaginary part." If α, γ and ϵ, as well as β and ζ, are real, as is the case for purely electric fields, the five "Seidel aberrations" familiar from ordi-

nary optics are obtained. The anisotropy of the magnetic fields introduces the three additional, "anisotropic," aberrations, anisotropic coma, astigmatism and distortion. It should be remarked that, in order to make the terminology of the aberrations significant and their calculation convenient, the "aperture plane" A should be chosen as the (virtual) plane of the exit pupil, obtained by drawing the tangents to the principal rays at their intersection with the image plane back to the point where they intersect the axis, as is shown in Fig. 12.

In examining these aberrations their character, their magnitude and the possibility and means of reducing and, eventually nullifying them, are primarily of interest. The theoretical examination of the individual aberrations has led to the following conclusions of a general nature.

(1) The aperture defect cannot be made zero for any electron lens (Scherzer[22]), but may, for given magnification and aperture angle, be reduced below any prescribed limit (Rebsch[23]).

(2) For purely magnetic lenses curvature of field cannot be made zero, but there are field configurations for which coma, distortion and astigmatism vanish individually (Voit[24]).

(3) For purely electric lenses all aberrations with the exception of the aperture defect may be made to vanish simultaneously; furthermore, for given aperture and magnification the total third-order aberration may be reduced below any prescribed limit (Voit[24]).

The above statements assume the possibility of constructing electrode and magnet configurations of unlimited fineness and, furthermore, do not take account of the possibility of enhancing higher order aberrations. If restrictions are placed on the field variations to make them both usable and realizable in practice, definite lower limits for some of the aberrations may be established.

The aperture defect or spherical aberration is the only one of all the geometric aberrations which does not disappear on the axis. Hence it is of primary interest in such cases as the production of fine spots by an electron gun, as well as in the electron microscope, where the field imaged is very small. Glaser[25] has calculated the least spherical aberration for a short, symmetrical magnetic lens with a bell-shaped field distribution, obtaining for $H=ke^{-|z|/a}$, where k and a are constants,

$$\zeta=\frac{b}{f^3}\left\{0.66\frac{f}{D}+0.45\left(\frac{f}{D}\right)^2\right\}, \quad f/D\geqslant 2.5. \tag{28}$$

Here b is the image distance, f the focal length and D the "length" of the lens, defined by

$$D=\int_{-\infty}^{\infty}H^2dz/H_{\max}{}^2. \tag{28a}$$

More favorable results may be obtained with lenses whose field is not restricted to a region short compared with their focal length. Rebsch[23] has considered a number of both magnetic and electric lenses, assuring the possibility of realizing them in practice by imposing a restriction on the maximum field variation:

$$|H'/H|_{\max}\leqslant 1/f; \quad |\Phi''/\Phi'|_{\max}\leqslant 1/f. \tag{29a}$$

Conditions are most favorable when the field is a maximum at the surface of the object. The best distributions yield, approximately,

$$\zeta=b/(4f^3). \tag{29b}$$

Actual measurements of the spherical aberration of a conventional electrostatically focused gun have been carried out and published by D. W. Epstein.[26]

Curvature and astigmatism resemble the aperture defect in so far as they, also, produce an aberration figure symmetric about the Gaussian image point. In general it is an ellipse whose axes are proportional to the square of the separation of the object point from the axis and to the first power of the aperture radius. If either β or γ vanishes it is a circle. Furthermore, if γ vanishes a sharp image is formed on an image surface tangent to the image plane on the axis and having a radius of curvature

$$R=-m^2/(2\beta Z), \tag{30}$$

where m is the magnification and Z the separation of the aperture and image planes. If $\gamma\neq 0$ there is no sharp image point except on the axis. While for ordinary astigmatism and curvature one of the axes of the aberration ellipse is always radial, it may, in the presence of anisotropic astigmatism, have any orientation. Curvature and astig-

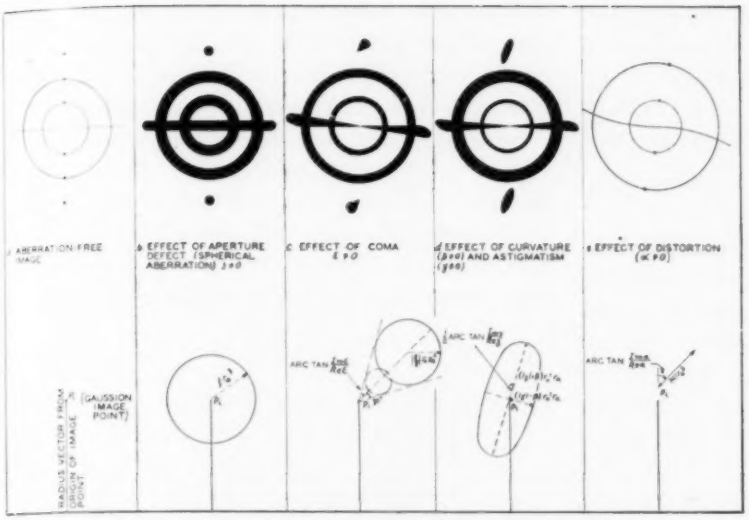

a ABERRATION-FREE IMAGE
b EFFECT OF APERTURE DEFECT (SPHERICAL ABERRATION) $\beta \neq 0$
c EFFECT OF COMA $\xi \neq 0$
d EFFECT OF CURVATURE ($\beta \neq 0$) AND ASTIGMATISM ($\xi \neq 0$)
e EFFECT OF DISTORTION ($\alpha \neq 0$)
ARC TAN
RADIUS VECTOR FROM AXIS OF IMAGE TO GAUSSIAN IMAGE POINT

FIG. 13. The effect of the individual geometric aberrations on the image.

matism are very serious defects in the imaging of extended objects, as in the image tube.[27, 28] Here giving the cathode a suitable curvature has proved effective in reducing them to a harmless degree.

The remaining geometrical aberrations, coma and distortion, are asymmetric about the Gaussian image point. The aberration figure in the former case is confined to a 60° sector, whose vertex coincides with the Gaussian image point and whose diameter is proportional to the square of the aperture radius and to the first power of the separation of the object point from the axis. In the presence of anisotropic coma this aberration figure, normally symmetric about the radius vector from the axis, may have any orientation.

Distortion, on the other hand, does not depend on the aperture coordinates and hence does not affect the sharpness, but only the shape of the image. It causes a displacement of the image point proportional to the third power of the object point from the axis. This displacement is radial for ordinary distortion, tangential for pure anisotropic distortion.

Both coma and distortion can, in principle, be made zero. In particular, any imaging system with unity magnification in which the electric and magnetic fields are antisymmetric about a central plane normal to the axis is free from these aberrations. Voit[24] has shown that this is true for weak lenses of this type even if the magnification is other than unity. An antisymmetrical field of the type mentioned may be realized by a magnetic lens consisting of two similar coils traversed by equal but oppositely directed currents. The effective aperture is assumed to be in the plane of symmetry.

Figure 13 shows the effect of the individual aberrations on a simple geometrical pattern together with enlarged representations of the aberration figures.

Another type of aberration, i.e., that due to the variation in the initial velocities of the electrons, must now be considered. As the electron index of the refracting field depends on the electron velocity, this is properly termed chromatic aberration. Scherzer[22] has shown that there is no space-charge free electron lens system free from chromatic aberration—the slower electrons starting from an axial object point invariably intersect the axis again at a place closer to that point than the faster electrons. Chromatic aberration can, however, be corrected, with the aid of an electron mirror, as is shown schematically for a plane mirror (a uniform retarding field) in Fig. 14. The strongly convergent beam A of slow electrons and the less strongly convergent beam A' of fast electrons are brought to the same focus F after "reflection" at the mirror.

For special cases formulas can readily be given for the circle of confusion due to chromatic aberration. Thus, for a purely magnetic lens its diameter is given by

$$d=(D/f)(\Delta\Phi/\Phi)b, \qquad (31)$$

where D/f is the aperture ratio of the lens, $e\Delta\Phi$ the deviation of the initial energy from the value $e\Phi$ for which the lens is focused and b the image distance. If, on the other hand, the object is the cathode with an accelerating field Φ_0' at its surface and all of the electrons emitted by a point on the axis take part in the imaging process

—such as is the case in the image tube—the chromatic aberration, together with the spherical aberration, from which it can scarcely be separated in this case, gives rise to a circle of confusion with a diameter approximately equal to

$$d = 2m\Delta\Phi/\Phi_0', \tag{32}$$

where $\Delta\Phi$ now describes the range of the initial velocities of the electrons. Thus to minimize chromatic aberration the initial energy range should be made as small and the initial field as large as possible. Henneberg and Recknagel[29] have shown that the increase of the chromatic aberration off the axis is not serious in the image tube under normal circumstances.

It would lead too far to discuss in any detail the effect of space charge on image quality. Quite generally space charge plays a negligible rôle in the imaging of extended objects as by the image tube or the electron microscope, as here the space charge densities are very low. It does, however, play a rôle in the production of fine, high current beams, as e.g. in the television receiver projection tube. This question has been treated thoroughly recently by v. Borries and Dosse.[30] The repulsion of the electrons causes a spreading of the beam which, for relatively low current densities, is proportional to the diameter of the beam, to the current density, the square of the length of the

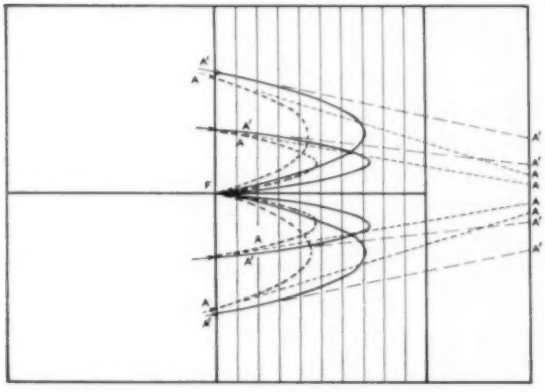


FIG. 14. Chromatic correction by a plane electron mirror.

beam and inversely proportional to the $\frac{3}{2}$ power of the volt velocity of the electrons.

7. *Applications of Electron Lenses*

Two important applications of electron lens systems in the field of television will now be considered. First among these is the electron gun in the iconoscope and in the viewing tube. This produces the fine electron spot which scans the mosaic and the luminescent screen, respectively. A very simplified form of such a gun is shown in Fig. 15. The electrons leaving the indirectly heated oxide-coated cathode C are accelerated and focused by the field penetrating from the first anode A_1 through the grid cylinder G into the "crossover," where the electrons leaving the

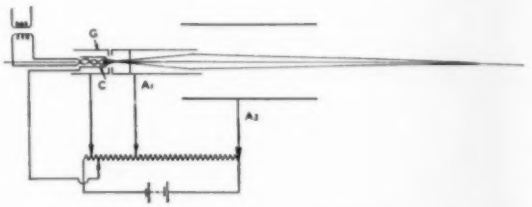


FIG. 15. Simple type of electron gun.

cathode with zero initial velocity cross the axis. This crossover, where the beam cross section is a minimum, is then imaged by the "final focusing field" produced between the first and second anode cylinders on the mosaic or screen. An apertured disk acting as screen grid is frequently inserted between the control grid and the first anode to minimize the effect of changes in the control grid potential on the position of the crossover and hence on the spot size. Masking apertures in the first anode serve to limit the aperture of the beam and thus to reduce the effect of spherical aberration and to intercept scattered electrons.

In the iconoscope a very fine and clean spot is essential. This can be attained, in view of the smallness of the beam currents required, by relatively simple means, such as long first anode cylinders and fine apertures. The greatest difficulties are encountered in the design of a gun for the projection tube, in which an extremely bright picture must be formed on a luminescent screen area of $2.4'' \times 1.8''$ which is then projected on a large screen.[31, 32] The problem is to obtain the largest possible current in a spot of a diameter dictated by the picture size and the required resolution. In the projection tube here considered this spot diameter d is about 0.25 mm. The aperture at the crossover, of which the spot is an image, must hence, by the ordinary laws of optics, have a radius

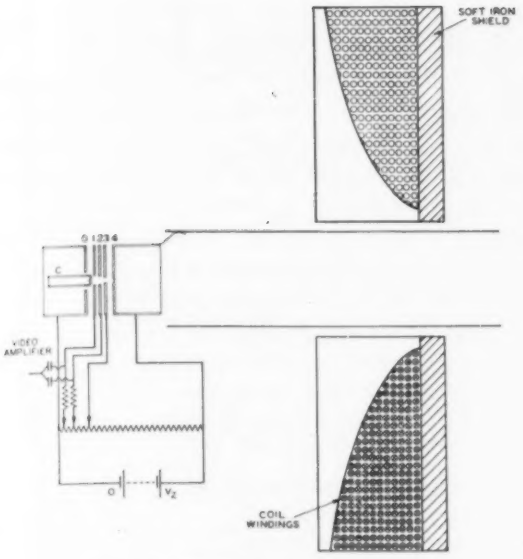


FIG. 16. Projection tube gun (law).

$$r=(d/2)(u/v)(\Phi_2/\Phi_1)^{\frac{1}{4}}, \qquad (33)$$

where u is the distance between the crossover and the final lens and v the distance between the final lens and the screen. Φ_2 and Φ_1 are the potentials of the second anode and first anode (crossover aperture), respectively. Here the maximum value of u is effectively fixed by the maximum aperture of the final lens which can be used without excessive spot enlargement due to spherical aberration or which is cleared by the tube neck, the minimum value of v by the available deflecting power. The size of the gun neck is controlled by the deflection yoke. Now, as Law[32] has shown, the portion of the space current I_s passing through a crossover aperture of radius r is given by

$$I=I_s[1-e^{-ar^2\Phi_1}]=I_s[1-e^{-b\Phi_2}]. \qquad (34)$$

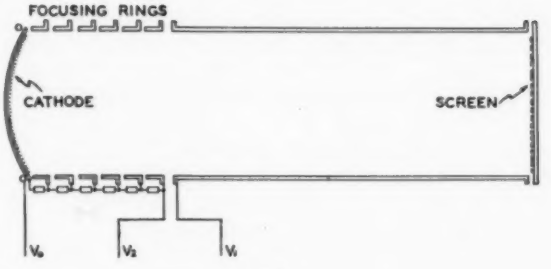
Here a is a constant depending on the cathode temperature and the field distribution between cathode and crossover and

$$b=a(e/2)^2(u/v)^2. \qquad (35)$$

Thus the fraction of the space current reaching the spot is independent of the first anode voltage, and depends only on the total applied voltage Φ_2. As, on the other hand, the space current, being space-charge limited, should be given approximately by const. $(D/s)^2\Phi_1^{\frac{1}{4}}$ where D is the cathode diameter and s the separation between cathode and crossover, the highest current density in the spot is obtained if $\Phi_1=\Phi_2$, i.e., if the full available voltage is applied to the crossover aperture. This consideration among others led to the design of the gun shown in Fig. 16, where the final lens is a magnetic lens of special form, minimizing spherical aberration; a soft iron plate shields its field from that of the deflecting coils. The electrodes 1 and 2, in combination, act as control grid. With this gun Law was able to obtain beam currents of 2 milliamperes at 10,000 volts concentrated in a spot 0.3 mm in diameter.

Another electron-optical device which has been of considerable significance in television development is the image tube, of which an electrostatic type is shown in Fig. 17. A photographic objective projects a scene on the photocathode which then emits electrons in a number proportional to the local brightness of the picture. These are accelerated and refocused by an electron lens

(a)



(b)

FIG. 17. Electrostatic image tube. (a) View of tube, (b) diagram and connections.

on the screen. If, as in the example shown in the figure, this is luminescent, the electrons will form a visible image of the original scene, while if it is the mosaic of an iconoscope, they will create a charge image of the scene thereon, which may be

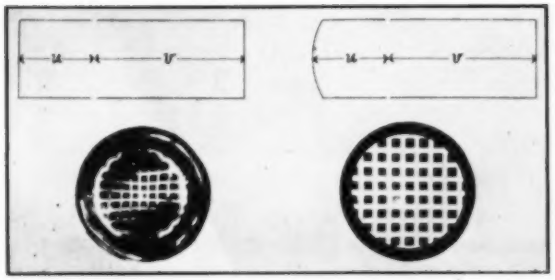


FIG. 18. Images produced by a flat and curved cathode image tube.

converted into picture pulses by the scanning process. In the electrostatic image tube shown provision is made for applying a small focusing voltage V_2 across a series of rings connected by resistors placed between the cathode and the anode cylinder, which is at potential V_1. The magnification is given approximately by $v/2u$, where v is the distance between the screen and the juncture between the last ring and the anode cylinder (the "lens"), while u is the distance from the cathode to this juncture.

In the image tube, unlike the electron gun, the image fields are large and the apertures small, the latter being determined by the range of the lateral initial velocities of the photoelectrons rather than by the geometry of the tube electrodes. Hence the image defects of greatest importance are the field aberrations, curvature, astigmatism and distortion, which, with a flat cathode, become very serious.[28] Fortunately they can be corrected quite adequately by giving the cathode a radius of curvature equal, approximately, to the separation of the cathode and the anode cylinder, as is shown by the images of similar object patterns obtained with a flat cathode and a curved cathode image tube shown in Fig. 18. With image tubes employing magnetic electron lenses adequately flat images have been obtained even without curving the cathode, although here, also, the field aberrations—in particular anisotropic distortion—prove troublesome.

The use of electron-optical principles in the design of deflecting fields, secondary emission multipliers and amplifier tubes has already been mentioned. These, like the two examples just considered, not only play an important rôle in the perfection of the technical aspects of television, but have already found many other applications. Perhaps the most interesting development of electron optics standing outside of the field of television, the electron microscope, has scarcely been touched. Even so it is evident that electron optics will be a tool of increasing usefulness to the physicist and engineer and, possibly, even wider circles.

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Luminescent Materials

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1. General Survey[2]

A LARGE number of crystalline materials become strongly luminescent whem bombarded by electrons or alpha-particles or when irradiated with ultraviolet light. We shall discuss the properties of a few of these, restricting our attention to inorganic materials, which alone are of interest for television since they are most able to withstand steady electron bombardment.

Only a few of the inorganic luminescent materials are of practical interest. Some of the factors that eliminate the rest may be listed as follows.

1. The efficiency of production of light may be too low. The best materials have quantum efficiencies close to unity for optical excitation and over-all energy efficiency of about ten per-cent for electron bombardment.

2. The emitted light may lie in a visibly inefficient part of the spectrum. The most valuable materials, at least at present, emit in the visible spectrum, near the peak of the visibility curve. Many luminescent materials emit a large part of their radiation in the ultraviolet or infra-red.

3. The emitted radiation may extend over such a wide range of wave-lengths that the fraction in a visibly efficient region is negligible.

As a specific example, the qualities necessary for a good commercial cathodoluminescent material are listed as follows: (1) Reasonable visible efficiency (greater than two candlepower per watt) in the temperature range 10°–200°C. (2) Useful color to produce pleasing light. (3) Short phosphorescence. (4) Stability during comminution and coating within tube (including "nonallergy" to common volatile constituents of cathode-ray tube parts). (5) Stability during exhaust at temperatures as high as 500°C. (6) Stability under cathode-ray bombardment. (7) Invariant spectral distribution. (8) Easy outgassing. (9) High "limiting potential." (10) Low absorption in the spectral region 4000–7000A.

Among the factors that influence the luminescence of a given substance, temperature is one of the most important. Generally speaking, emission bands become narrower and the over-all energy efficiency increases with decreasing temperature. In fact many materials that show negligible luminescence at room temperatures are strongly luminescent and have almost monochromatic spectra at low temperatures. Silver chloride, which has been investigated at low temperatures by Randall[3] along with a number of other substances, is a typical luminescent material of this type. The luminescent efficiency *versus* temperature curves of many phosphors behave[4] like the curve of Fig. 1, which is for a zinc-cadmium sulphide phosphor. The tempera-

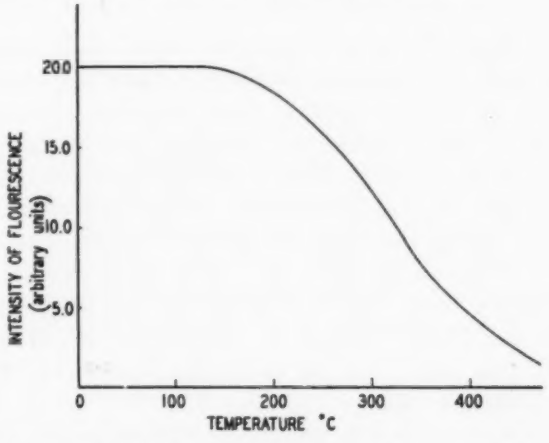


Fig. 1. The variation of luminescent efficiency of a zinc-cadmium sulphide phosphor with temperature. (Randall.) The ordinates are in arbitrary units.

ture at which the efficiency begins to drop is different for different materials, being well below room temperature in the case of silver chloride. From this we may conclude that many more luminescent materials would be of practical value if they were used at low temperatures.

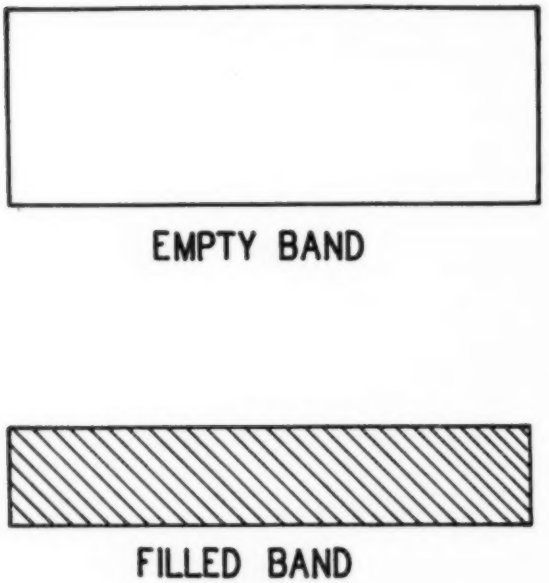


FIG. 2. The filling of bands in insulators, according to the band theory of solids.

Except for several important cases, the experimental investigation[5] of luminescent materials has been restricted to such practical questions as preparation, excitation energies, and emission wave-lengths and efficiencies. For this reason, the experimental facts that are essential for a reasonably accurate interpretation in terms of atomic processes are known in only a few cases. We shall discuss these cases in most detail, but shall also include other important luminescent materials that probably will be understood more fully in the near future.

For reference in the following discussion, we shall at this point distinguish between an ideal crystal, a pure crystal, and an impure crystal.

(a) By an ideal crystal we shall mean one that contains no impurities and has ideal structure and composition. For example, an ideal crystal of zinc sulphide is one in which the combining atomic ratio of zinc and sulphur is exactly unity, in which all atoms are arranged at the sites of either the sphalerite or wurtzite lattice (Fig. 7), and in which no sites are unoccupied.

(b) A pure crystal is one that contains no impurities. The composition need not conform to ideal stoichiometric ratios nor need the lattice be perfect. For example, alkali halide single crystals ordinarily contain a small fraction (10^{-6}) of vacant halogen and alkali ion sites.

(c) An impure crystal is, of course, one that contains impurity atoms.

Ordinary, pure, crystalline materials are not ideal because of either one or both of the following reasons: (i) They may consist of many single crystals. This is true, for example, of the powders formed by aqueous precipitation or of ordinary solidified melts. (ii) The lattices of the individual single crystals may not be perfect. Lattice imperfections of this type occur in the alkali halides, as mentioned in (b) above.

In a state of complete thermodynamical equilibrium any group of single crystals would join into one large single crystal. This usually does not happen in a reasonable time at room temperature because the rate at which different crystals interchange material is extremely small. As most substances are heated, however, their vapor pressures increase and the rate at which equilibrium is attained becomes faster. For this reason there usually is a temperature above which equilibrium may be attained in a reasonable time, such as a few days. Thus a quantity of

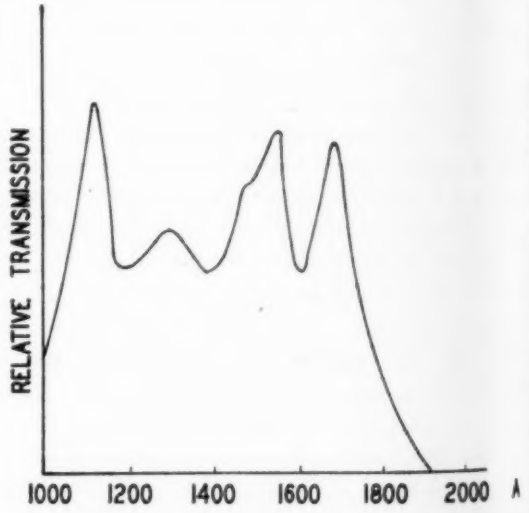


FIG. 3. The absorption bands of ideal sodium bromide crystals showing the sharp absorption peaks.

finely powdered zinc sulphide is transformed into a few comparatively large crystals if it is left in a closed container at 800°C for several days. It may be concluded that the type of deviation from idealness corresponding to case (i) above may be made as small as one desires by using a suitable heating technique. On the other hand, a good deal of experimental evidence, which is discussed in more detail in Section 2, shows that defects of type (ii) increase rather than decrease with increasing temperature. In other words, large single crystals become less perfect when heated. In the following work, we shall refer to this type of imperfection when we use the terms lattice imperfection or lattice defect.

It has been found in several cases that the more ideal specimens of crystals that form the base of luminescent materials such as the alkali halides are not nearly as strongly luminescent as

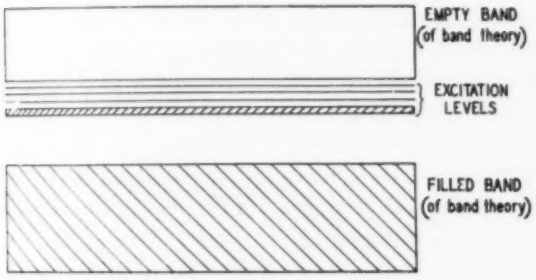


FIG. 4. More accurate scheme of levels in insulating salts. The upper and lower bands correspond to those shown in Fig. 2. The intermediate levels correspond to excitation states in which the excited electron and the hole it leaves in the lower band do not move independently.

those that contain more lattice defects. It is possible that these cases are examples of a general rule which would state that ideal crystals are not luminescent under ultraviolet radiation.

Another fact that is valid often enough to class as a rule is that the wave-length of luminescent light that is induced by radiation is longer than that of the exciting radiation. This is commonly known as Stokes' law. Anti-Stokes luminescence has been observed, but we shall have no cause to discuss these exceptional cases.

2. *Brief Theoretical Discussion*[6]

In this section we shall present briefly some of the theoretical concepts that are important for understanding crystal luminescence.

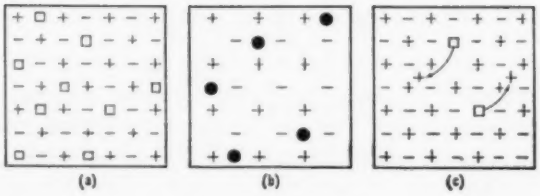


FIG. 5. Lattice defects in several types of crystals: (a) In the alkali halides vacancies occur in both lattices and there are no interstitial atoms or cores. (b) In zinc sulphide and zinc oxide there are no vacancies, but excess metal atoms diffuse into interstitial positions. (c) In silver halides, atoms leave ordinary sites and diffuse into interstitial positions.

(a) THE ELECTRONIC STRUCTURE OF IDEAL CRYSTALS

According to the zone theory of solids, which was described in an earlier issue of this journal, the valence electrons in ideal crystals of simple nonconductors completely fill a band of levels in the manner shown in Fig. 2. If this theory were strictly accurate, the first absorption bands of salts should be very broad bands, even at very low temperatures; moreover this absorption should be accompanied by photoconductivity. A detailed investigation[7] of the alkali halides, however, shows that they do not behave in this way. Instead, their first absorption bands are fairly narrow at low temperatures (see Fig. 3 for NaBr). For this reason the energy level diagram has been modified as is shown in Fig. 4 by the introduction of several bands between the filled band and the first unoccupied band of Fig. 2. The new[8] levels correspond to states in which the excited electron and the hole left in the lower band remain at a finite distance from one another so that the crystal does not become conducting. The coupled hole and electron move about the crystal as a wave of excitation. For this reason, the coupled pair is called an exciton.[8] It is believed at present that the first ultraviolet absorption bands of the alkali halides are related to the production of excitons and that the absorption band corresponding to the transition between the bands of Fig. 2, or to ionization, is relatively weak and lies on the far ultraviolet side of the absorption region of Fig. 3. It is not yet certain, however, that the same conclusion can be drawn for the salts of divalent metals such as zinc sulphide or zinc silicate.

(b) Lattice Defects in Pure Materials

It was mentioned above that the crystals of salts such as the alkali halides show deviation from ideal form. The principles that underlie the existence of these lattice defects were studied experimentally and theoretically by[9] Hilsch, Pohl, Schottky, Wagner and their co-workers, and can be reduced to applications of principles of ordinary chemical equilibrium. We shall not discuss these principles in detail here, but we shall point out some of the conclusions that have been drawn in special cases.

(i) The alkali halides contain vacancies in both the positive and negative ion lattices (Fig. 5(a)). If the crystal is heated in a vacuum, the two types of vacancies increase in equal number because of an increase in the rate of diffusion of ions from the interior of the crystal to the surface. Concentration of vacancies of the order of 10^{19} per cc have been obtained at temperatures near the melting point. The number of alkali ion vacancies is depressed if the crystal is heated in alkali metal vapor. A crystal that contains an excess of alkali metal usually is colored, exhibiting a narrow absorption band in the visible

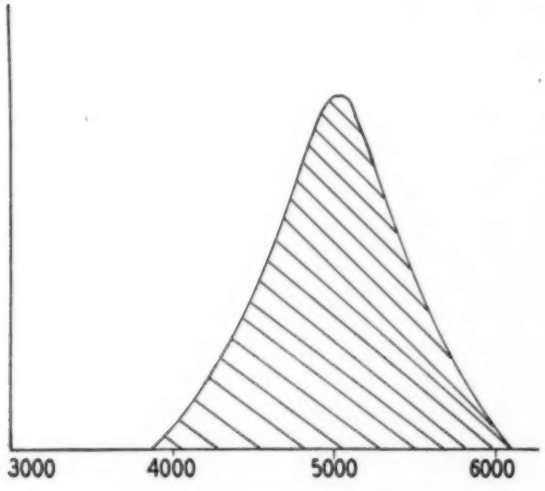


Fig. 6. The absorption band of colored rocksalt.

(see Fig. 6). This band is not associated with the excess alkali metal ions, but with the free electrons that must accompany them if the crystal is unchanged.

(ii) The lattice defects that occur in zinc oxide are considerably different from those of the alkali halides. In this case, oxygen ions do not diffuse appreciably within the crystal; however, those near the surface evaporate leaving an excess of neutral zinc atoms that diffuse into the interstices of the porous lattices (Fig. 7(b)). The crystal becomes brown in color, as this process proceeds, because the interstitial atoms absorb in

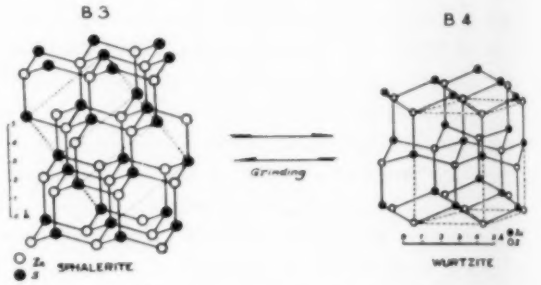


Fig. 7. The sphalerite and wurtzite lattices. Zinc oxide also forms in the wurtzite structure.

the visible region. The ratio of interstitial atoms to normal atoms may become as large as 10^{-3} if the crystal is heated to temperatures in the vicinity of 1000°C. Since zinc oxide and zinc sulphide are chemically similar substances and have similar structures, it can be assumed[18] that the defects that occur in the sulphide are the same as in the oxide.

(iii) The silver halides, silver chloride and silver bromide, have the same structure as the alkali halides. Indirect evidence shows,[9] however, that the defects that occur in these salts are different from those that occur in the alkali halides. In this case silver ions leave normal lattice sites and enter interstitial ones, as is shown in Fig. 5(c).

The presence of lattice defects usually alters the electronic energy spectra of pure materials by adding new levels. The most direct evidence for this is the fact that crystals such as the alkali halides with excess alkali metal atoms and zinc oxide with interstitial zinc atoms are colored. Generally speaking, the detailed origin of the additional levels must be considered separately in each solid. Unfortunately, the amount of experimental information that is required to obtain such a detailed interpretation is available only in a few cases. In the case of the alkali halides, it has been fairly definitely established[19] that the additional levels may be associated with

the valence electrons of the excess alkali metal ions which are normally localized at vacant halogen ion sites, where they are simultaneously bound to six neighboring alkali ions. Some of these electrons are freed by light quanta falling in the absorption band of Fig. 6, so that we may conclude that these normal levels lie just below the unfilled band of the zone scheme, as is shown

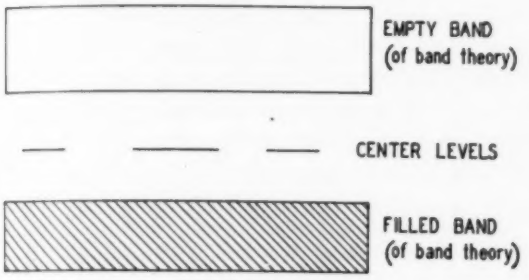


FIG. 8. Additional electronic levels in alkali halides and zinc oxide crystals having defects.

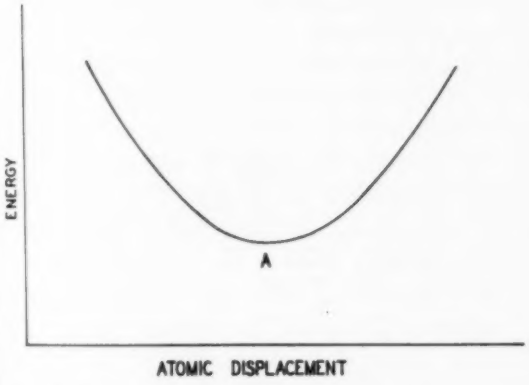


FIG. 9. Variation of energy with atomic displacements (schematic). The point A corresponds to the position of stable equilibrium.

schematically in Fig. 8. Similarly, the discoloration of zinc oxide results from the absorption of light by the electrons that surround the interstitial zinc atoms. Since these electrons are also nearly free, the diagram of Fig. 8 also applies to them.

(c) Impure Crystals

Impurity atoms may add to the crystal energy levels that are similar to those resulting from lattice defects. For example, there is abundant evidence[11] to show that copper, silver and other atoms may diffuse into the interstices of

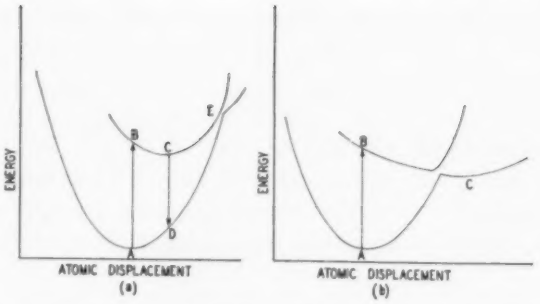


FIG. 10. Variation of energy with atomic displacement for a normal and an excited state. In case (a) the minimum of the excited state lies within that of the lower state and luminescent radiation may occur. This is not possible in case (b).

zinc oxide and zinc sulphide and give rise to levels similar to those shown in Fig. 8. Similarly, if impurity ions are substituted for the ions of the pure material at ordinary lattice positions, the impure crystal may exhibit additional absorption bands that may be associated with the electrons of these impurity ions. We shall discuss cases of this kind in the next section in connection with alkali halide luminescent materials.

For convenience, the impurity atoms and lattice defect atoms will be called centers. This connotation is commonly used in discussing luminescent crystals.

(d) The Coupling Between Electrons and Lattice

In an attempt to interpret the absorption and emission properties of crystals it is important to appreciate the fact that a crystal is a large molecule that has vibrational as well as electronic energy states. Let us suppose, for example, that the crystal is in its normal electronic state and that the atoms are at their equilibrium positions. If the atoms or ions are displaced, the energy of the entire crystal varies as is shown schematically in Fig. 9. The minimum corresponds to the stable atomic arrangement and the other values of the abscissa to other arrangements. The corresponding curve for another electronic state usually is different for displacements in the neighborhood of an excited atom because the forces between normal and excited atoms are different. Hence the minimum for an excited electronic state may be displaced relative to the

minimum for the normal state (Fig. 10). The fact that the frequency of luminescent radiation usually is less than that of the stimulating radiation can be understood in terms of this principle. In the case of Fig. 10(a), the system makes a vertical transition from the equilibrium position A of the lowest state to the point B of the excited state during absorption of light.

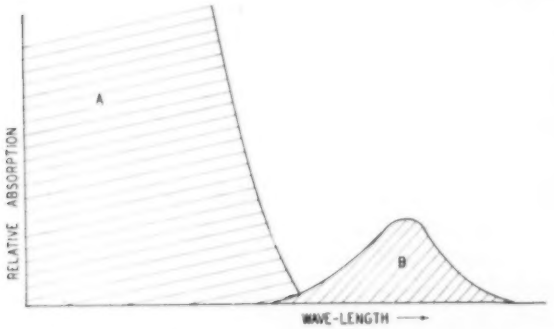


FIG. 11. Customary separation of fundamental absorption band A and center absorption band B. In this case, the center absorption band lies near the foot of A, but does not completely overlap with it. The absorption in A is usually of the order of a thousand times larger than in B.

Only vertical transitions occur[12] because atoms do not move appreciably during the time required for electronic excitation. Before light emission can occur enough time elapses for the system to move from B to the equilibrium position C of the excited state. The energy corresponding to the difference between B and C is dissipated in the form of elastic waves. Optical emission then occurs during the jump C to D. It should be clear from this diagram that the emission frequency cannot be greater than the absorption frequency unless the system is further excited before jumping from C to D.

The breadth of the emission and absorption line is determined by the amplitude of thermal vibration about the equilibrium position, such as A and C. In the case of Fig. 10(a), the system may reach the point B, if the amplitude of oscillation is large enough, and may then cross to the lowest electronic level without emitting any optical radiation. It should then move from E to A emitting all of the stored energy as elastic waves. Since the amplitude of oscillations increases with increasing temperature, this transition without luminescence should be more probable at high temperatures than at low. Gurney and Mott[13] have used this principle to explain high temperature decreases in luminescent efficiency such as that illustrated in Fig. 1.

(e) Absence of Luminescence in Ideal Crystals

The nearly complete absence of luminescence in some ideal crystals can be explained in at least two ways. First, it is possible that observations have been made at temperatures too high for the luminescent process to be very probable. Second, it is possible that the normal and excited levels have the form of Fig. 10(b). In this case, the equilibrium state C is at a position where there is no lower state to which it may jump.

(f) The Relative Positions of Fundamental Absorption Bands and Those of the Centers

It was seen above that electronic levels may be added to any ideal crystal by lattice defects or by impurity atoms. In most of the cases in which we shall be interested, these additional levels induce additional absorption bands that are on the long wave-length side of the fundamental absorption band, as in Fig. 11. The absorption coefficient in these added bands usually is much smaller than in the fundamental band because the ratio of the number of lattice defects or impurity atoms to the number of atoms of the bulk material is usually 10^{-3} or less. In some cases, as in the alkali halides, of which large single crystals can be obtained, it is possible to measure the additional absorption bands by direct transmission measurements. In other cases,[14] as in zinc cadmium sulphide, it has been possible to detect their presence qualitatively by reflection measurements from powders.

If the fundamental and center bands are definitely separated, as in Fig. 11, it is possible to separate the luminescence that is induced by direct excitation of the center from that induced by direct excitation of the bulk material. In all of the cases that will be discussed the absorption region for most efficient production of luminescence is the center band B of Fig. 11. If the crystal is pure, luminescence is not observed during illumination in A. Luminescence is some-

times observed during this excitation, however, when the crystal has centers, the luminescent radiation being the same as that obtained by direct absorption in B. We may conclude that in these cases the energy absorbed by the bulk material from radiation lying in A is transferred in some way to the centers. Since the excitation associated with the fundamental bands corresponds either to the production of free electrons or to the production of excitons, it may be concluded that these particles act as the carriers of energy.

(g) The Difference Between Cathode-Ray Excitation and Optical Excitation

The process of irradiating a crystal with electrons or with alpha-particles is qualitatively the same as irradiating it with a continuous spectrum of optical frequencies extending from the infrared to the wave-length that corresponds to the maximum cathode-ray energy. Thus the relative amount of excitation of any given kind that the crystal receives under cathode-ray bombardment is proportional to the optical absorption coefficient for the corresponding optical process. Now it was seen in the foregoing discussion that the absorption coefficient of the center absorption band is much smaller than that of the fundamental band. Hence most of the cathode-ray energy should go into exciting the bulk material For example, if the ratio of centers to ordinary atoms is 10^{-3} or 10^{-4}, only one part in 10^3 or 10^4 of the energy of the cathode rays should be absorbed by direct collisions with the centers. If only collisions of this type could stimulate luminescence, the over-all efficiency of cathode luminescence in these cases should be a tenth of a percent, or less. Actually, efficiencies a hundred times larger than this are common. This fact supports the statement made in Part (f) that secondary electrons or excitons may excite centers. (See the paper quoted in reference 11.)

Crystal luminescence of the type stimulated by optical absorption in the band B of the center can be excited by x-rays and by α-particles, as well as by cathode rays. It is probable that in these cases, as in the case of cathodoluminescence, that the bulk material absorbs the energy and electrons or excitons are responsible for the actual excitation of the centers.

3. *Properties of Particular Luminescent Materials*

(a) Alkali Halides

Ideal alkali halide crystals, as we have remarked previously, do not seem to show appreciable luminescence under ultraviolet radiation, which indicates that the absorbed energy is dissipated in the form of elastic waves.

Alkali halide crystals containing excess alkali metal atoms have additional absorption bands in the visible and near ultraviolet spectrum. The writers are not acquainted with experiments that show unambiguously that these crystals luminesce when irradiated with light lying in these absorption bands.

The most widely studied luminescent alkali halide crystals are those produced by adding a small amount of a halide of a heavy metal such as thallium, bismuth, silver or lead. The fractions added are usually of the order of magnitude 10^{-4}. Particular attention has been given to the thallium activated salts by Hilsch,[15] Pohl and

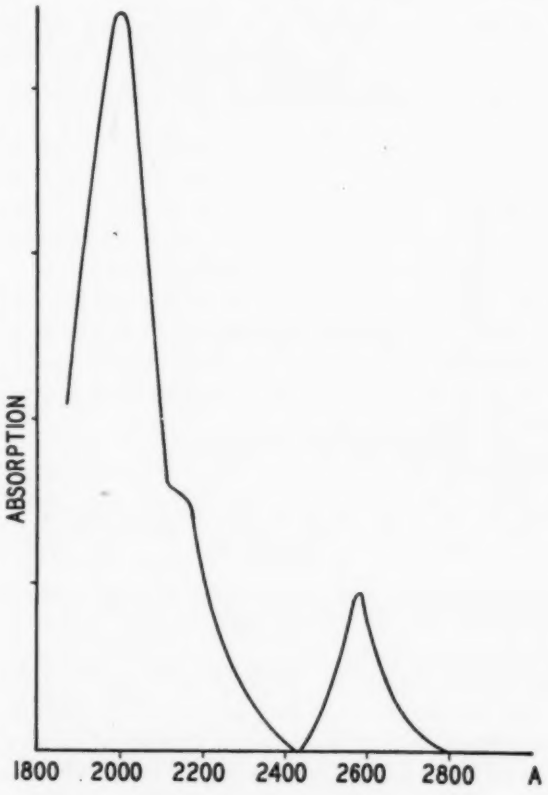


Fig. 12. The thallium absorption band in the thallium phosphors.

their numerous collaborators. These materials are highly efficient under optical excitation but they have not been used extensively because they are not efficient under cathode-ray bombardment, and they cannot withstand the vigorous treatment that they would receive in common applications. Their properties may be summarized as follows.

1. The monovalent thallium and alkali metal halides seem to be perfectly miscible in the concentrations that occur in the luminescent materials. Hence in these substances we have to do with alkali halide lattices in which occasional alkali metal ions are replaced by single charged thallium ions.

2. The luminescent crystals have several narrow absorption bands in the ultraviolet region between 3000A and 2000A which may be correlated with the electronic levels of the free ions. The structure of these bands is illustrated in Fig. 12 for sodium chloride plus thallium.

3. The emission peaks lie in the near ultraviolet and visible region of the spectrum and are stimulated by absorption in the bands of Fig. 12. Practically all of the radiation is emitted within 10^{-5} second after excitation. This luminescence

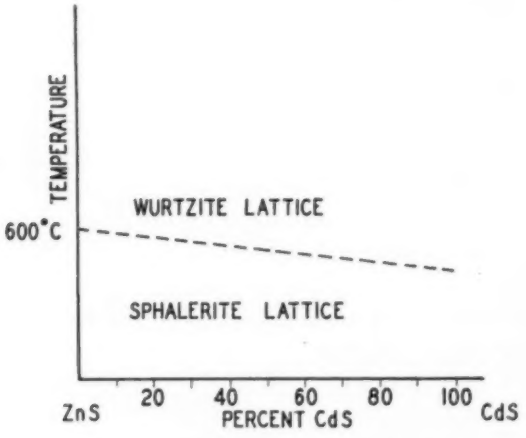


FIG. 13. Schematic phase diagram of the zinc-cadmium sulphide system.

may be explained in the same way as the resonance fluorescence of free atoms. The thallium ions jump to excited states as a result of absorption of light and, after coming to equilibrium in the excited state, re-emit light quanta. The emitted frequency is lower than the absorbed one for reasons discussed in Part (d) of Section 2. Thus the thallium ions behave like the free atoms of a gas with the exception that they lose some of their excitation energy to the lattice with which they are coupled.

4. These thallium phosphors exhibit a faint phosphorescence that may be associated with the small fraction of thallium ions that have thallium ions as nearest positive ion neighbors. We shall not discuss this phosphorescence in detail.

5. Since no photoconductivity is observed in these luminescent materials, it follows that no electrons are freed from the thallium ions during excitation. This is in agreement with the preceding interpretation of the luminescence in terms of simple excitation of the thallium ions.

This simple picture probably needs modification for the other alkali halide luminescent materials, such as those activated by lead or silver, since there is evidence to show that the foreign atoms do not simply substitute for alkali metal ions in these cases. Instead, they seem to congregate into more complex molecular groups. These substances have not been examined thoroughly enough to make it possible to say whether or not the same type of excitation and emission mechanism is valid.

The alkali halide phosphors may also be excited by cathode-ray bombardment, but quantitative measurements of the efficiencies are not available.

(b) Other Halide Phosphors

Randall[4] has found that many simple chlorides such as cuprous chloride, silver chloride and thallous chloride are luminescent at low temperatures. These salts probably could be subjected to the same type of investigation that has been carried out in the alkali halides and zinc sulphide. There is not yet sufficient experimental material, however, to allow any conclusion about the detailed atomic processes to be drawn.

(c) Zinc Sulphide and Its Derivative Phosphors

Zinc sulphide is the basic material for the most widely investigated[16] and best known group of luminescent materials. The luminescent properties of the salt were discovered by Sidot in 1869.

We shall discuss the zinc-cadmium sulphide system since it can be treated as a unit. The properties may be summarized as follows.

1. Zinc and cadmium sulphide form a completely miscible system of salts that have sphalerite structure of Fig. 7(a) at low temperature and change to the wurtzite structure of Fig. 7(b) above 600°C. The thermodynamic transition temperatures of the system have not been measured, but probably are close to 600°C (see Fig. 13).

2. The crystalline material formed by precipitation methods show neither photoconductivity nor appreciable photoluminescence. It is possible that this is in some way connected with the fact that this material is in a finely divided state, but it is also possible that the individual crystals are so nearly ideal that they do not contain many luminescent centers.[17]

The bulk absorption band of pure zinc sulphide begins[14] at about 3150A and extends to the Schumann region. This band does not seem to show the same type of detailed structure that is observed in the alkali halides. Pure cadmium sulphide begins to absorb in the red end of the visible spectrum and the mixed salts begin to absorb between the limits of the two pure salts at a point that depends upon the composition.

3. The pure mixed salts show luminescence after being heated for several hours at 900°C, or for a longer time at lower temperature. This luminescence is light blue for pure zinc sulphide and lies in the infra-red for pure cadmium sulphide. Peaks at any wave-length between

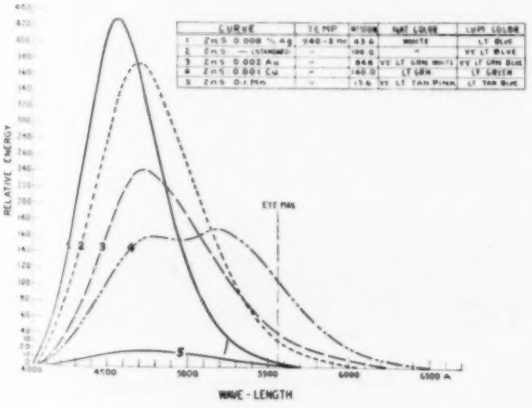


FIG. 14. The emission spectra of several zinc sulphide phosphors.

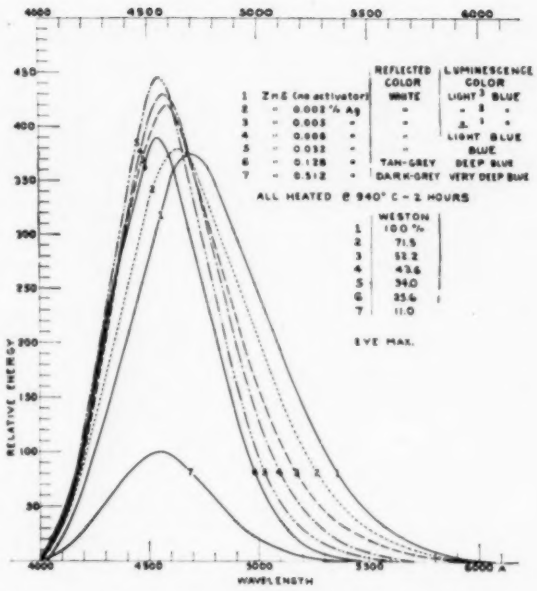


FIG. 15. Influence of silver content on emission spectrum of zinc sulphide phosphor.

these two limits may be obtained by properly mixing the two salts (see Figs. 14, 15 and 16). The peaks for excitation of this luminescence lie in the near ultraviolet, being at 3650A for pure zinc sulphide and nearer the visible in the other cases. A reasonable picture[18] of the activation process of the pure salts is that they lose sulphur and gain interstitial atoms during heating. These interstitial atoms, which are the luminescent centers, behave in a way that will be described in more detail below.

4. The luminescent color of a given mixed salt may be changed by heating the salt with a small trace of the salts of other heavy atoms, such as silver, copper, gold or manganese. The sulphides of these activating metals do not form solid solutions with zinc and cadmium sulphide. Figs. 15 and 16 show, respectively, the luminescence of pure zinc sulphide and of a fifty-fifty mixed salt as the silver content is varied. It should be observed that the emission curve of the mixed salt is changed by the addition of one-millionth part of silver! This is an illustration of the hypersensitivity of the luminescent properties of the sulphide phosphors to impurity atom content —a fact that makes it extremely difficult to reproduce their characteristics even under the cleanest possible working conditions. It is com-

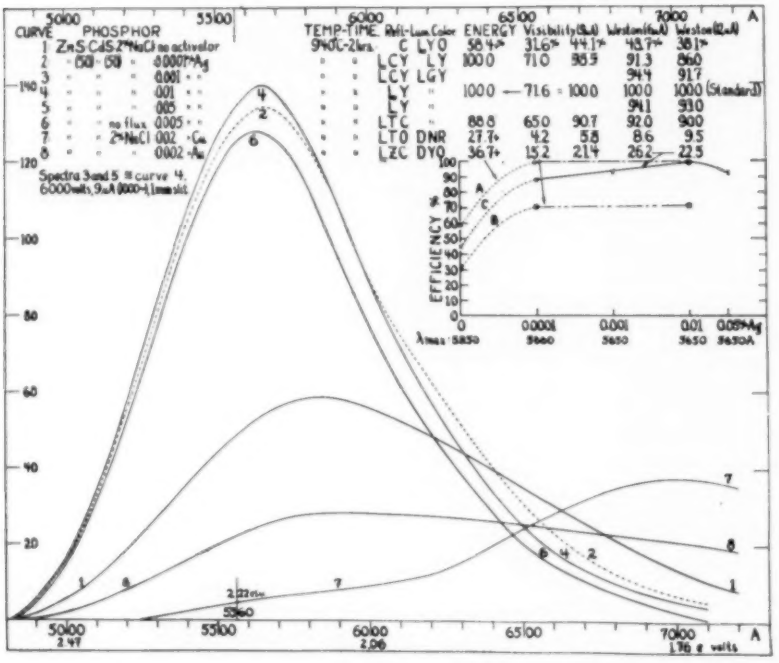


FIG. 16. Influence of activator content on emission spectrum of ZnCdS phosphors. It should be observed that one part per million of silver affects the emission curve.

mon practice to mix a flux, which consists of a pure salt, with the luminescent materials during heating, and to evaporate or wash this out of the crystals later. The shape of the excitation and emission curves of the final product depend markedly upon the type of flux used. The physical and chemical principles that govern these variations are not fully understood at present.

It seems most likely that the activating atoms enter into the interstitial positions along with atoms of the pure salt in these impure materials.

5. The luminescent efficiency of many of the zinc-cadmium sulphide phosphors is comparatively high. Thus the quantum efficiency for optical excitation of the copper-activated zinc sulphide is close to unity and the cathode-ray efficiency is above ten percent.

The region of most efficient optical excitation lies at the long wave-length foot of the fundamental absorption band of the pure salt. Since reflection measurements show that the absorption in this region at the foot of the fundamental band is greater in the luminescent salts than in the unheated ones we may conclude, at least tentatively, that the absorption bands of these materials resemble those shown in Fig. 8. Photoconductivity accompanies luminescence so that we may conclude that the interstitial atoms become ionized during the absorption process. The spectral-sensitivity curve for photoconductivity is nearly identical with the curve for excitation of luminescence.

6. The luminescent sulphides are phosphorescent, that is, they continue to emit light after excitation has stopped. This is exactly what we should expect if luminescence is connected with the recombination of the electrons and ions that become separated during excitation, for it may be shown that the recombination process should take a measurable time. The temperature dependence of this phosphorescence may be explained in a qualitative way on the basis of the recombination hypothesis, but quantitative agreement has not yet been demonstrated.[19]

7. The characteristic luminescence of the zinc-cadmium sulphides may be stimulated strongly by optical radiation below 3000A which lies near

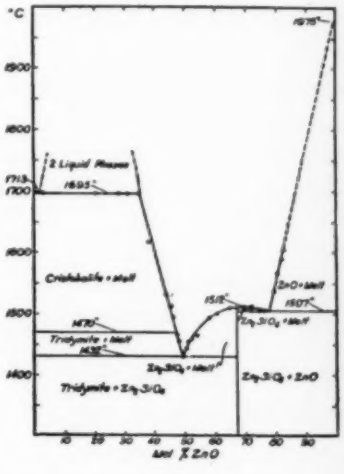


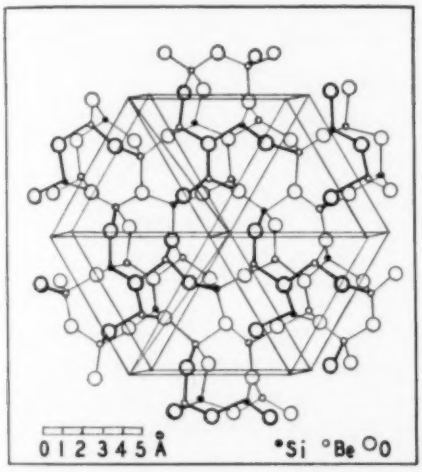
FIG. 17. The zinc oxide-silica phase diagram. The α-, β-, and γ-phases of zinc orthosilicate are not indicated.

the center of the fundamental absorption region. As we remarked in Section 2, Part (f), only a negligible fraction of these light quanta can excite the centers directly so that most of the excitation must occur either by excitons or by secondary electrons.

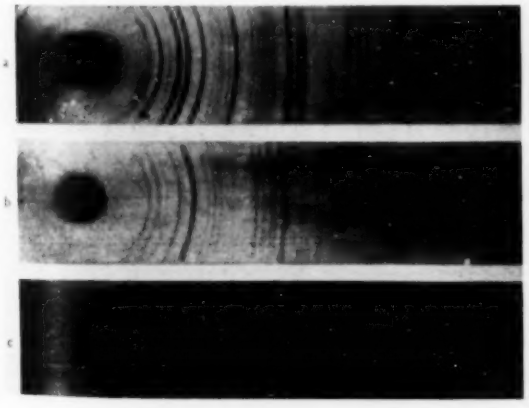
(d) Zinc Silicate and Some of Its Derivative Phosphors

Figure 17 is the phase-diagram of the zinc oxide-silica system as determined by E. N. Bunting of the National Bureau of Standards.[20] The pertinent information to be noted in this diagram is that only one chemical compound, zinc orthosilicate—having a ratio of two zinc oxides to one silica—is formed with a melting point of 1512°C.

The left side of Fig. 18 shows the crystal lattice structure of zinc orthosilicate which is isomorphous with beryllium orthosilicate. The three x-ray power photographs of Fig. 18 taken from Schleede and Gruhl,[21] are three polymorphic forms of zinc orthosilicate, i.e., they are three distinct crystal lattice structures in which the one substance, zinc orthosilicate, may crystallize without any alteration of chemical constitution. The upper photograph corresponds to the normal- or alpha-structure shown at the left, whereas the other two photographs are of crystals obtained by rapidly cooling molten zinc silicate. The center, beta-form, reverts to the top, alpha-form, if heated at about 900°C, whereas the less stable gamma-form (lower photograph) reverts to alpha as low as 300–400°C.



(A)



(B)

FIG. 18. The crystal structure of a zinc orthosilicate. This is a typical silicate structure. Also x-ray diffraction pictures of the three zinc orthosilicate phases (Schleede and Gruhl).

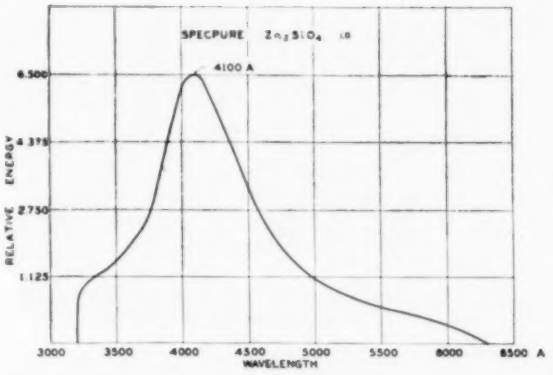


FIG. 19. The emission curve of pure zinc orthosilicate.

Spectroscopically-pure, alpha-zinc silicate, crystallized without any additions, has the pale blue cathodoluminescence spectrum shown in Fig. 19. This spectrum, which is broadly peaked at 4100A, is obtained, unaltered in form or efficiency from all zinc-silicates whose formulae range from strictly ortho-proportions to that of the material containing one hundred percent excess silica, as long as the substance is crystallized in the α-form. The spectrum of Fig. 19 was measured by photographing the light transmitted through a Pyrex Kinescope (approximately 4-mm thick glass wall). There is reason to believe

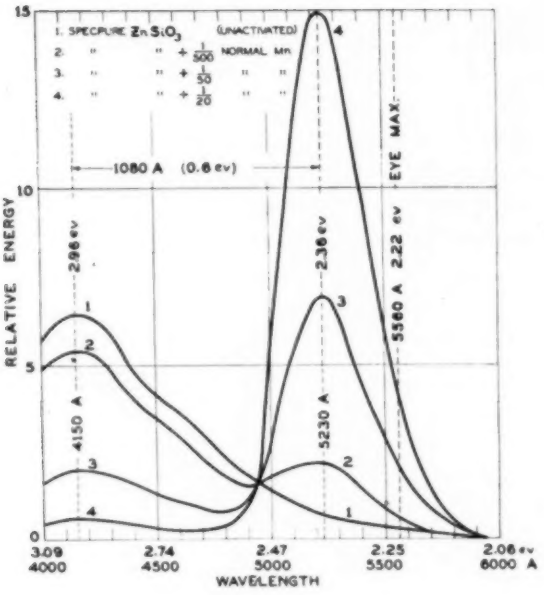


FIG. 20. The dependence of the emission curve of α willemite on manganese concentration.

that the spectrum rises even higher in the ultraviolet than in the visible.

Figure 20 shows the transition from pure, i.e., unactivated, zinc silicate to manganese-activated zinc silicate. The pure substance's feeble emission spectrum vanishes by degrees, and an enormous relative increase in emitted energy is obtained as the activator concentration is increased up to one percent.

Continuing the picture of activation, Fig. 21 demonstrates the effect of excess manganese above the normal optimum. A gradual, small displacement of the emission spectrum toward longer wave-lengths is accompanied by a decrease in emitted energy. The observed emission color changes from blue-green to yellow-green.

Figure 22 shows the emission spectrum of manganese-activated beta-zinc silicate which is contrasted with the chemically identical but crystallographically dissimilar alpha-willemite. The beta-willemite has a strong canary-yellow emission color.

Figure 23 demonstrates the effect of substituting germanium for silicon in the alpha-willemite structure. The alpha-zinc germanate phosphor also has a yellower green color than normal alpha-willemite.

A much greater variety of spectra may be obtained by partially substituting other metals for zinc in alpha-willemite. In particular, the isomorphic substitution of beryllium for zinc, as

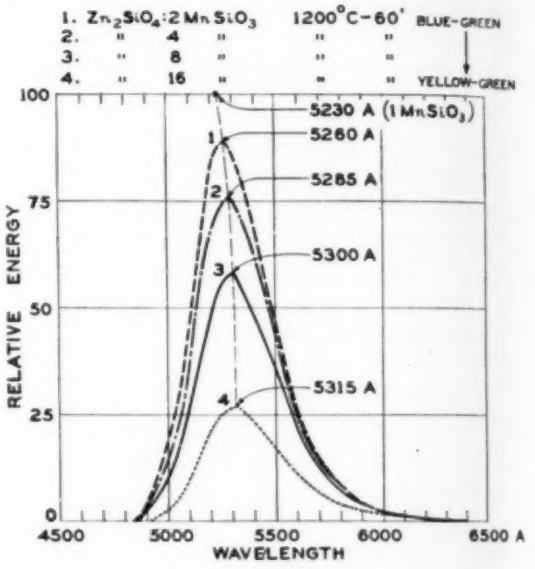


FIG. 21. Extension of Fig. 21.

shown in Fig. 24, gives a large number of useful colors ranging from blue-green to red-orange. The beryllium substitution flattens the alpha-willemite spectrum and shifts it toward the red. The zinc-beryllium silicate system has a much

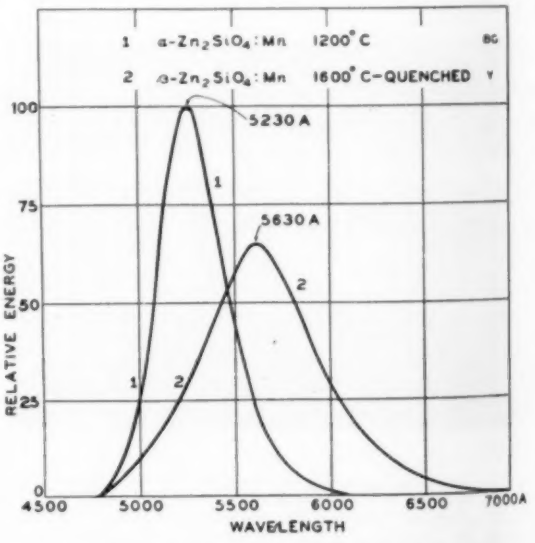


FIG. 22. The emission spectrum of β-willemite.

greater sensitivity to variation of composition, crystallization temperature and time than the practically unchangeable zinc silicate system. Fig. 25 demonstrates the sensitivity of the system to manganese activator variation whereas Fig. 26 demonstrates the strong dependence of zinc-beryllium silicates on crystallization temperature. The second property is foreign to alpha-willemite.

The inclusions of periodic-group-four silicates, namely, titanium-, zirconium-, hafnium- and thorium-silicates, in the zinc-beryllium silicates produces an emission in the violet end of the spectrum. The group-four silicates are not isomorphous with zinc- and beryllium-silicate. The resultant phosphor system is even more susceptible to temperature and composition changes

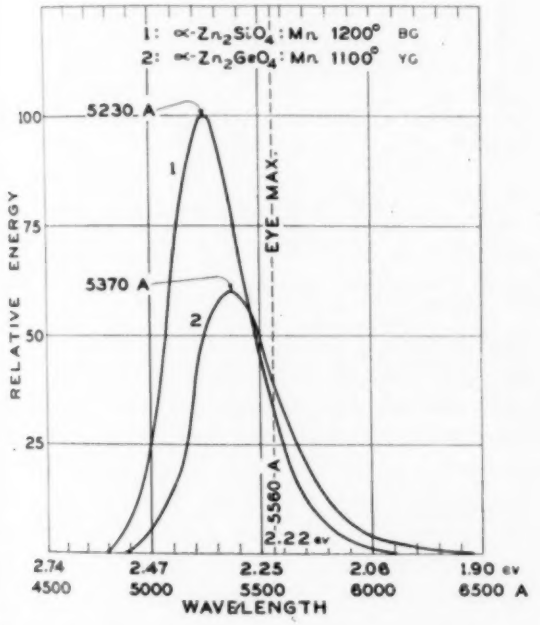


FIG. 23. A comparison of the emission spectra of silicate and germanate phosphors.

than the zinc-beryllium silicate system. The red-enhancement that is obtained by beryllium substitution is retained during these additions. Fig. 27 shows the emission spectra of several of these complicated phosphors, some of which correspond to almost white emission colors.

It is worth re-emphasizing that the individual curves that are shown for the zinc beryllium silicate phosphors, are only examples from the general phosphor system. The spectral emission curves of the zinc beryllium silicate system can be varied by infinitesimal amounts within the color range from blue-green to red-orange.

The stoichiometric formulae, shown on all the spectral distribution curves, represent the ap-

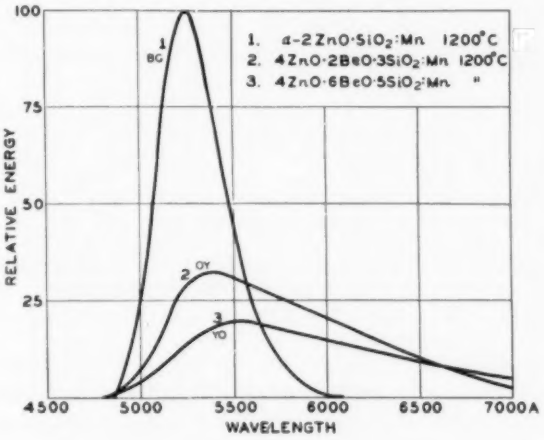


FIG. 24. The emission spectra of some zinc beryllium silicates.

proximate proportions present before crystallization. These phosphor-formulae cannot be given an accurate interpretation without giving detailed descriptions of the experimental technique employed in preparing a particular phosphor, in which we shall not indulge here.

2. The fundamental absorption spectra of the orthosilicates have not been investigated very thoroughly, so that it is not possible to say with

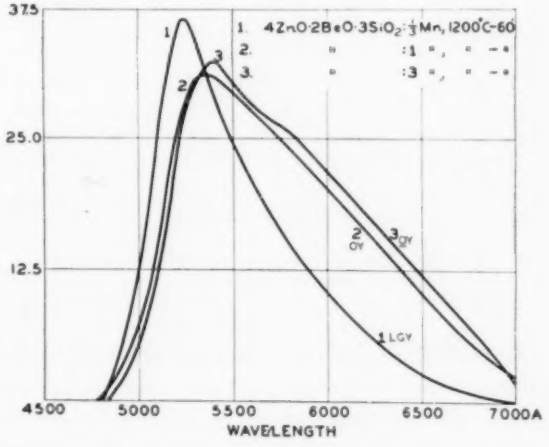


FIG. 25. The dependence of the emission spectrum of a zinc beryllium silicate phosphor on manganese concentration.

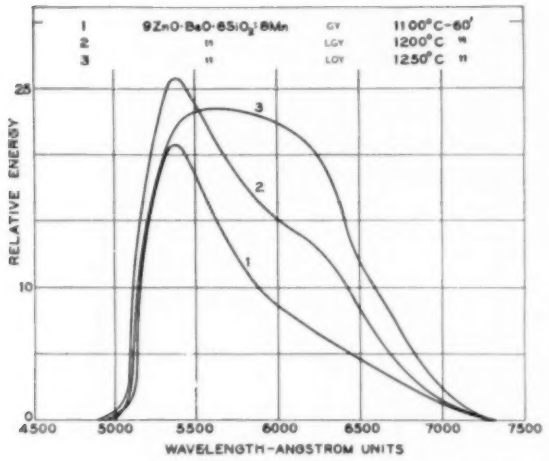


FIG. 26. The dependence of emissivity of a zinc-beryllium silicate phosphor on crystallization temperature.

certainty that the peaks for excitation of luminescence in these materials should be associated with defects or impurities. A rough measurement[22] of the transmission of thin sections of natural willemite crystals at 2537A indicates, however, that the damping coefficient is of the order of 10 cm^{-1}. Since this wave-length lies at the center of the first peak for excitation of luminescence, it seems very probable that this peak does not lie in the fundamental absorption region. The Schumann region excitation bands, however, probably lie in these bands.

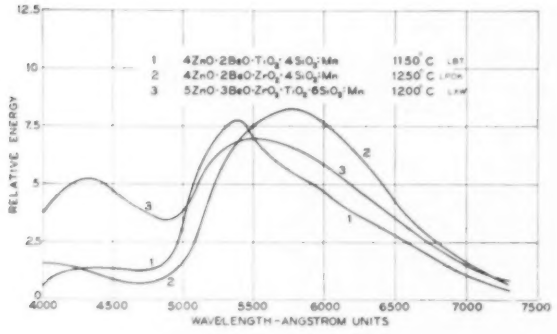


FIG. 27. The emission spectra of group-four silicate phosphors.

3. Willemite becomes photoconducting[23] when luminescence is excited in the first ultraviolet band, showing that electrons are freed from the center as in the sulphide phosphors. The decay characteristic of the luminescence of the sulphides and of the silicates are considerably different, however, so that it is not possible to establish a close analogy between the two types at present.

4. Any proposed mechanism for the luminescence of the silicates does not rest on as good an experimental basis as the mechanisms given above for the alkali halide and zinc-cadmium sulphide phosphors. In spite of this, it seems safe to make the following remarks that are based on the experiments for willemite.

(a) It may be concluded that the luminescent center is a neutral unit such as a neutral metal atom or a neutral oxygen atom, for otherwise it would be difficult to explain the relatively low ionization energy of the center.

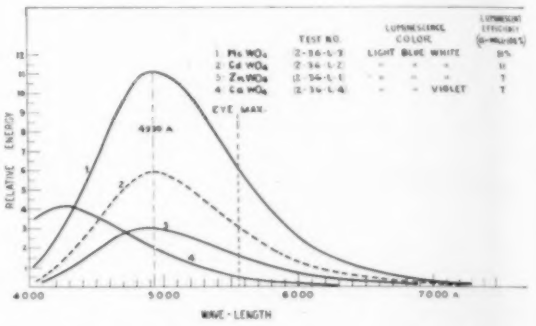


FIG. 28. The emission spectra of some tungstate phosphors.

(b) Since the internal oxygen ions in silicates are tightly bound, as are the oxygen ions in zinc oxide and the sulphur ions in zinc sulphide, it seems most probable that the defects are either interstitial metal atoms, as in the sulphides, or are neutral oxygen atoms that are near vacancies left by metal atoms that have diffused away. Many silica glasses show a positive ion conductivity that indicates that positive ions move either by means of vacancies or through interstitial positions.

(e) TUNGSTATES

The pure alkaline earth tungstates and tungstates of other divalent metallic elements, $MgWO_4$, $CaWO_4$, $ZnWO_4$, $CdWO_4$, which are produced by heating the metal oxide with tungstic oxide, are luminescent under cathode-ray excitation. The characteristic emission spectra, which consist of broad bands, are shown in Fig. 28. These materials are useful because, like the

silicates, they can withstand intense bombardment. Their physical properties have not been widely investigated, however, so it is not possible to advance an interpretation of their spectra.

(f) Other Phosphors formed from Compounds of Divalent Metals

Many salts of divalent elements, such as zinc oxide, calcium sulphide, calcium oxide and barium sulphide are luminescent. In particular, Ewles[24] has recently found that calcium oxide may be activated by a large number of impurities. Those salts of this type that have zinc sulphide structure usually behave very much like zinc sulphide and probably are activated by interstitial atoms. Others, such as calcium oxide, have more closely packed lattices, however, and probably involve a different type of mechanism.

Bibliography

1. The spectral distribution curves in Sections 3(c)–3(e) are taken from papers presented before the American Physical Society, Washington, D. C., Paper No. 30, April, 1938, and the American Optical Society, Niagara Falls, Canada, October, 1938. The recording instrument is described by V. K. Zworykin, J. Opt. Soc. Am. **29**, 84 (1939).
2. Many important quantitative experiments on cathode-ray excitation and phosphorescence, such as those of Nottingham, Johnson and Nelson will not be discussed in this article. (Cf. J. App. Phys. **10**, 73 (1939).)
3. J. T. Randall, Gen. Elec. Co. Journal, England **8**, 103 (1937); Proc. Phys. Soc. **49**, 46 (1937).
4. J. T. Randall, Nature **142**, 113 (1938); Trans. Faraday Soc. **35**, 1 (1939).
5. Surveys of experimental material may be found in the books by Lenard and Tomaschek, *Handbuch der Experimentalphysik* (Akademische Verlagsgesellschaft, Leipzig, 1928), and by H. Rupp, *Die Leuchtmassen und Ihre Verwendung* (Borntraeger, Berlin, 1937). See also the issue of the Faraday Society which is quoted in reference 4.
6. A more complete discussion of this material may be found in this journal, **8**, 246 (1937), and in the issue of the Transactions of the Faraday Society which is quoted in reference 4.
7. R. Hilsch and R. Pohl, Zeits. f. Physik **48**, 384 (1928); E. G. Schneider and H. M. O'Bryan, Phys. Rev. **51**, 293 (1937).
8. This was first pointed out by J. Frenkel, Physik. Zeits. Sowjetunion **9**, 158 (1936).
9. R. Pohl. See the review articles in Proc. Phys. Soc. **49**, (sup.) 3 (1937). Schottky and Wagner. Zeits. f. Physik. Chemie **B11**, 136 (1931). A survey may be found in the book of Jost: *Diffusion und Chemische Reaktionen in Festen Stoffen* (Theodor Steinkopff, Dresden, 1937).
10. J. H. deBoer, Rec. Trav. Chem. Pays-Bas **56**, 301 (1937); R. W. Gurney and N. F. Mott, Proc. Phys. Soc. Supp. **49**, 32 (1937).
11. Evidence for the diffusion of atoms in zinc sulphide has been given by N. Riehl, Ann. d. Physik **29**, 663 (1937).
12. This is known as the Franck-Condon principle.
13. R. W. Gurney and N. F. Mott, Trans. Faraday Soc. reference 6.
14. See article in the second paper of reference 6.
15. A survey of this work is given by Hilsch in the supplement of Volume 49 of the Proceedings of The Physical Society. See also J. Chem. Phys. **6**, 150 (1938).
16. A. Schleede, Angewandte Chemie **48**, 270 (1935); *ibid.* **50**, 908 (1937). W. Kutzner, Zeits. f. Physik **106**, 551 (1937). S. Rothschild, Zeits. f. Physik **108**, 24 (1937). K. Kamm, Ann. d. Physik **5**, **30**, 333 (1937). N. Riehl, Ann. d. Physik **5**, **29**, 636 (1937). B. Bartels, Dissertation (Leipzig, 1936).
17. This view is strongly supported by work of D. H. Kabakjian, which will be published soon, and which shows that comparatively large water-grown crystals of $BaSO_4$ and $BaBr_2$ luminesce only after being heated.
18. This picture has been presented independently by A. Schleede, Angew. Chemie **50**, 908 (1937), and F. Seitz, J. Chem. Phys. **6**, 454 (1938).
19. Unpublished work of R. P. Johnson, however, has gone a long way toward furnishing this agreement.
20. E. N. Bunting, Nat. Bur. Stand. J. Research **4**, 131–136 (1930).
21. Zeits. f. Elektrochemie u. Ang. Physik. Chemie **27**, 411–12 (1923).
22. Performed by F. Quinlan of The General Electric Research Laboratories.
23. R. Hofstadter, Phys. Rev. **54**, 864 (1938).
24. J. Ewles, Trans. Faraday Soc. **35**, 119 (1939).

Resumés of Recent Research

Recent advances in experimental and theoretical physics are described in these columns in nontechnical language. It is intended that sufficient background be given to introduce the reader to the subject.

X-Ray Study of Changes that Occur in Malleable Iron during Fatiguing

It is highly desirable, from a theoretical as well as a practical point of view, to know just what changes in internal structure take place in metals as they are fatigued. X-ray diffraction patterns offer a possibility of studying these changes. A few men have made such studies but the results have been somewhat conflicting. Recently, Raymond G. Spencer,[1] at Albion College, has reported studies on malleable iron.

Spencer fatigued carefully prepared specimens of malleable iron and took x-ray diffraction patterns of them as fatiguing progressed. He worked with some specimens that were fatigued at a stress below their endurance limit. The specimens were fatigued in an ordinary rotating beam machine. The camera was made so that it produced one diffraction line with good speed and detail. The changes that took place in the structure of this line in the successive patterns, taken at intervals as fatiguing progressed, revealed the changes that occurred in the specimen.

The results indicate that, when malleable iron is fatigued below its endurance limit, no changes occur in its internal structure after the first few cycles of fatiguing. When it is fatigued above its endurance limit, appreciable rotation of the grains on the surface and some splitting of the grains may occur in the first few cycles of fatiguing. Changes then occur very slowly during the major part of the fatiguing process. As the specimen approaches failure very marked grain distortion occurs followed by fragmentation of some of the grains to a small enough size to approach random orientation. This distortion and partial fragmentation always precedes failure whether the specimen is fatigued at a stress very much above, or only slightly above, its endurance limit. The formation of fatigue cracks makes very fine fragments of all the grains adjacent to the fatigue cracks.

[1] Raymond G. Spencer, "An X-Ray Study of the Changes that Occur in Malleable Iron during the Process of Fatiguing," Phys. Rev. **55**, 991 (1939).

Mechanism of Hearing

Since Volta first connected a battery of 30 or 40 cells to two metal rods inserted into his ears and received a jolt in the head followed by a noise like the boiling of thick soup, several experimenters have produced a sensation of hearing by passing an electric current through the head. Many theories have been proposed to account for this ability of the ear to respond to an electric current. Most theories have considered the inner ear as the seat of the conversion of electrical energy into mechanical vibration, chiefly because it is known that the cochlea is able to perform the reverse process, that of converting sound energy into electrical energy.

Our understanding of the process of hearing under electrical stimulation was considerably advanced in a recent paper by S. S. Stevens and R. Clark Jones,[1] who showed that the response of the ear is almost exactly proportional to the square of the voltage applied between a salt solution in the external ear-canal, and an electrode applied to the wrist. The consequence of this square-law response is that when the ear is stimulated by an alternating voltage the ear hears the second harmonic of the applied frequency. But when a polarizing direct current is applied along with the alternating current the listener hears the fundamental frequency as well

[1] S. S. Stevens and R. Clark Jones, "The Mechanism of Hearing by Electrical Stimulation," J. Acous. Soc. Am. **10**, 261–269 (1939).

as the second harmonic. The loudness of the fundamental depends on the strength of the direct current.

The authors propose that the square-law response can be ascribed to the electrostatic attractive force between the ear-drum and the opposite wall of the middle ear. Such a force has the necessary property of being proportional to the square of the potential difference. It is shown that the minimal potential detectable by the ear is approximately in quantitative agreement with that predicted by electrostatic theory.

The large amount of second-harmonic distortion which has previously prevented the understanding of speech and music when the listener is connected directly to the electrical output of a radio set can be greatly reduced by the application of a polarizing direct current. Under these conditions speech and music can be heard with great clarity. The authors report "a reasonably pleasant half-hour was spent listening to Fred Allen's program."

A New Method of Isotope Separation

There is a constantly increasing number of scientific uses for separated isotopes, or for samples of elementary or compound substances in which the ratio of the isotopes is markedly different from the natural ratio. In chemistry and biology such substances are often of decisive use as "tracers," and in nuclear physics they may serve to identify doubtful reactions or to increase the intensity of technically useful effects.

Various methods have been suggested for producing separation of isotopes, and several of them have been applied with considerable success. Chemical methods, such as the use of electrolysis or of solution equilibria, have been quite effective in several cases. Diffusion through porous tubes or into streams of mercury vapor has been employed. The method which bases itself most directly on the difference of molecular masses is the use of centrifuges.

A method which has recently attracted considerable attention depends upon still another phenomenon—that of *thermal diffusion*. Under static conditions this effect results in the establishment of a concentration gradient wherever there is a temperature gradient. For isotopes the concentration difference is only a fraction of one percent for a temperature difference of some hundreds of degrees. The effect can be made cumulative, however, by a continuous flow method, first used by Clusius and Dickel,[1] and also investigated by Brewer and Bramley.[2] The gas is contained in the space between two coaxial vertical tubes; the inner tube is heated, the outer one cooled. Thermal diffusion causes a difference in concentration between the rising and falling convection streams, and there results a continuous transport of the light isotope upward and the heavy one downward. Eventually the logarithmic concentration gradient *along* the tube may reach values as great as 0.01 *per centimeter*.

The mathematical description of the processes of convection and diffusion in such an apparatus has been worked out in detail in a recent paper by Furry, Jones and Onsager.[3] From this treatment definite predictions can be made as to the way the performance of the apparatus will depend on the dimensions, the pressure, and the compound used.

Among the many problems of separating isotopes of various elements for different purposes and to various degrees of purity, there are undoubtedly quite a number for which this method will be eminently suitable. In particular, it may be found that it is generally preferable for the heavier elements. All methods inevitably are less efficient for heavy elements than for light, but the difference is probably not as marked with the thermal diffusion method as with most others.

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[1] K. Clusius and G. Dickel, Naturwiss. **26**, 546 (1938); **27**, 148 (1939).

[2] A. K. Brewer and A. Bramley, Phys. Rev. **55**, 590(A) (1939).

[3] W. H. Furry, R. Clark Jones and L. Onsager, Phys Rev. **55**, 1083 (1939).

Contributors to This Issue

Ralph W. Dornte received his B.S. in Chemical Engineering from Purdue University in 1927 and Ph.D. in Chemistry from Princeton University in 1931. From 1931 to 1933 he was National Research Fellow in Chemistry at the University of California and since 1933 he has been with the Research Laboratory of the General Electric Company.

H. Kersten received his A.B. and M.S. degrees in Electrical Engineering in 1923 and 1924 from the University of Wisconsin, his M.A. in Mathematics from the University of Chicago in 1926, and his Ph.D. in Physics in 1938 from the University of Cincinnati. He is an Assistant Professor of Mathematics and is carrying on research work in crystal structure and biophysics in the Department of Physics at the University of Cincinnati.

George A. Morton received his B.S. in Electrical Engineering, his M.S. and Ph.D. degrees from the Massachusetts Institute of Technology in 1926, 1928 and 1932, respectively. He was research associate and instructor at M.I.T. from 1927 to 1933 and since 1933 he has been in the electronic research laboratory of the RCA Manufacturing Company, Inc.

H. Dunholter received his A.B. in 1935 and his Ph.D. in Physics in 1939 from the University of Cincinnati. He has been the Laws Fellow and Hanna Fellow in Physics at the University of Cincinnati and is now employed in the aerodynamics department of the Vultee Aircraft Company.

E. G. Ramberg received his B.A. degree at Cornell University in 1928 and his Ph.D. at the University of Munich in 1932. In the succeeding three years he was research assistant at Cornell University, engaged in theoretical work on x-ray spectroscopy. Since 1935 he has been with the Electronic Research Laboratory of the RCA Manufacturing Company.

Knox McIlwain received his B.S. degree from Princeton University in 1918 and his B.S. in E.E. and E.E. degrees from the University of Pennsylvania in 1921 and 1930, respectively. He worked in the engineering department of the Bell Telephone Company of Pennsylvania from 1921 to 1924; since then he has been on the faculty of the Moore School of Electrical Engineering of the University of Pennsylvania. He is an author of various technical articles, and of three books: *High Frequency Alternating Currents*, Knox McIlwain and J. G. Brainerd; and the two volumes of the *Electrical Engineers' Handbook*, edited by Harold Pender, Wm. A. Del Mar and Knox McIlwain.

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Humboldt W. Leverenz was born in Chicago, Illinois, in 1909. He received his B.A. degree from Stanford University in 1930. From 1930 to 1931 he was an International Institute of Education Exchange Student at the Universität zu Münster in Westphalen, Germany. Since 1931 he has been research chemico-physicist in the electronic research laboratory of the RCA Manufacturing Company, Inc., at Camden, New Jersey.

Pierre Mertz received his A.B. from Cornell University in 1918. Following a period with the American Telephone and Telegraph Company, he returned to Cornell, receiving a Ph.D. in 1926. He later joined the Bell Telephone Laboratories to work on telephotograph and television transmission.

Dr. Peter Carl Goldmark, Columbia's Chief Television Engineer who is responsible for television engineering activities and the installation of the television station atop the Chrysler Building, was born in Budapest, Hungary, December 2, 1906. He received his education at the University of Berlin and the University of Vienna graduating from the latter in 1930 with the B.Sc. and obtaining his Ph.D. in Physics in 1931. The same year he went to work for Pye Radio, Limited, in Cambridge, England, taking charge of the concern's television activities until 1933. He then worked for several years as consulting engineer and in 1936 joined the staff of CBS to direct research on television developments, two years later becoming Columbia's Chief Television Engineer. During the period of his association with Columbia Dr. Goldmark has had several scientific papers published in a number of scientific publications and has received several patents for his inventions, including the recently demonstrated synthetic reverberation device. He also has several patents still pending. Dr. Goldmark's favorite pastimes are television, music and sports.

David L. Webster received his Ph.D. degree in 1913 from Harvard, and taught there and at the University of Michigan and Massachusetts Institute of Technology and worked in applied physics in the Army before coming to Stanford in 1920, where he is now Professor of Physics. His principal research interests have been in the physics of x-rays.

D. L. Webster

Photographs of other contributors to this issue have already been published.

David Sarnoff's picture was used on p. 373 of Vol. 8, No. 6, 1937.

Frederick Seitz' picture was used on p. 72 of Vol. 8, No. 1, 1937.

New Books

Introduction to Bessel Functions. FRANK BOWMAN. Pp. 135+x, Figs. 21, 13½×21½ cm. Longmans, Green and Company, London, 1938. Price, $3.60.

This little work on Bessel Functions, their properties and applications, appears to be a useful short reference book for physicists. Of course, anyone wishing to study thoroughly the properties of these ubiquitous functions will have to refer to Watson's monumental treatise on the subject. However, Watson's *Bessel Functions* is out of print and the few copies obtainable command excessive prices; so that the present volume, even though it is more limited in its scope, is quite welcome.

Mr. Bowman treats the Bessel functions of order zero in much greater detail than those of other orders. His first chapter is on the general properties of the two "zeroth" order functions, and his second chapter on their application to vibration and diffusion. The third chapter is concerned with the zero-order Bessel functions of a complex argument and their application to high frequency electrical problems. The next two chapters are on integral representations and asymptotic expansions. A few of the useful discontinuous integrals involving Bessel functions are given here, with derivations which may not be perfect in their rigor or generality but which are the more valuable to physicists for their simplicity.

In the last two chapters are considered the functions of any real order, and a few of their applications. A number of the more useful recurrence formulas and integral expressions involving Bessel functions are worked out; the Fourier-Bessel series is discussed, together with its limiting integral; and a few of the possible applications are discussed. It is unfortunate that a few more of the integral expressions involving higher order functions could not be included here; and that some of the plane wave expansions so useful in scattering calculations are not discussed. One also misses a discussion of the application of half-order Bessel functions to spherical problems. An additional fifteen pages would have covered these additional subjects sufficiently for most readers. Such regrets about omissions, however, are not to be viewed as criticisms; for any omission is bound to disappoint someone, and a book cannot contain everything.

Mr. Bowman's book is to be commended for its clarity and its organization. The index is brief, but seems to be adequate. The typography is gratifyingly clean-cut and readable.

PHILIP M. MORSE
Massachusetts Institute of Technology

Here and There

Appointments and Promotions

Dr. Hans Reinheimmer has been made Professor of Spectroscopy at Boston College. He was with the Norddeutsche Kabelworke, Berlin, formerly.

★

Dr. Arnulf Liebetegger has been appointed as a part-time instructor in the Department of Physics at Brown University.

★

Dr. O. C. Simpson has been made an Assistant Professor of Physics at Carnegie Institute of Technology.

★

Dr. Russell H. Lyddane has been appointed Assistant Professor of Physics at the University of North Carolina, replacing Dr. James B. Fisk who goes to the Bell Telephone Laboratories.

★

Mr. C. H. Ehrhardt and Mr. R. E. Schreiber have been promoted from assistants to instructors in the Department of Physics at Purdue University.

★

Dr. Curtis W. Lampson has been promoted from instructor to Assistant Professor of Physics at the University of Richmond.

★

Dr. Robert Hofstadter of Princeton University has been appointed the George Leib Harrison research fellow in the Department of Physics for the year 1939–40 at the University of Pennsylvania.

★

Dr. Donald S. Bayley of the University of Iowa has been appointed assistant instructor for the year 1939–40 at the University of Pennsylvania.

★

National Research Council

The National Research Council recently awarded twenty-four National Research Fellowships in the Natural Sciences for the academic year 1939–1940, five of which are in the fields of Physics and Mathematics (none in Astronomy), as follows:

PHYSICS

Richard Henry Bolt (Ph.D. in Physics, University of California at Los Angeles, 1939). To work at Massachusetts Institute of Technology. Subject: The wave theory approach to room acoustics.

Myron Hiram Nichols (Ph.D. in Physics, Massachusetts Institute of Technology, 1939). To work at Princeton University. Subject: Thermionic work function of thoriated and caesiated tungsten for the different crystal faces.

Julian Seymour Schwinger (Ph.D. in Physics, Columbia University, 1939). To work at the University of California. Subject: The theory of nuclear forces.

Wave Henry Shaffer (Ph.D. in Physics, Ohio State University, 1939). To work at the University of Chicago. Subject: Interpretation of band spectra of polyatomic molecules.

MATHEMATICS

Orville Goodwin Harrold, Jr. (Ph.D. in Mathematics, Stanford University, 1936). To work at the University of Virginia. Subject: The structure of semi-schlicht images of a compact metric space with especial reference to $(K, 1)$ transformations. The topology of rectifiable curves.

★

At the annual meeting of the American Academy of Arts and Sciences the following fellows in mathematical and physical sciences were elected:

Bart Jan Bok, Harvard University.
Lyman James Briggs, the National Bureau of Standards.
Harry Edward Farnsworth, Brown University.
Clifford Burrough Purves, Massachusetts Institute of Technology.
C. Richard Soderberg, Massachusetts Institute of Technology.
Frank Clifford Whitmore, Pennsylvania State College.

★

Among the new members elected to the National Academy of Sciences at the annual meeting in Washington were:

Gregory Breit, Professor of Physics, University of Wisconsin.
Detlev Wulf Bronk, Johnson Professor of Biophysics and Director of the Johnson Foundation, University of Pennsylvania.
Zay Jeffries, General Electric Company, Cleveland, Ohio.
Sir William Bragg, Director, the Royal Institution of Great Britain and Fullerian Professor of Chemistry and Director of the Faraday Research Laboratory was elected foreign associate.

★

Dr. A. E. Kennelly, Professor Emeritus of Electrical Engineering of Harvard University and at the Massachusetts Institute of Technology, was elected on April 14 a member of the Royal Academy of Sciences of Upsala, Sweden.

★

Columbia University has conferred the title of Professor Emeritus in residence on Dr. Bergen Davis of the Physics Department.

★

Dr. David Sarnoff, President of the Radio Corporation of America, was among those who received a scroll of honor on April 19 from the National Institute of Immigrant Welfare. The award is given to "distinguished citizens of foreign birth who have made significant contributions to American life."

★

The Mittag-Leffler Institute Gold Medal of the Mathematical Institute at Stockholm has been awarded to M. Emile Picard, Professor of Mathematics in the University of Paris and permanent secretary of the Academy for Mathematical Sciences, Paris.

★

Dr. H. M. James has received a Guggenheim Fellowship in Physics for 1939–1940 and is going to be on leave of absence from the Department of Physics at Purdue University.

★

Assistant Professor Victor Weisskopf of Rochester University will be visiting professor at Stanford University this summer where he will give a course on Radiation and Electron Theory.

The John J. Carty Medal and Award for the Advancement of Science, consisting of a gold medal, bronze replica, certificate and $3000 in cash, was awarded to Sir William Bragg, of the Royal Institution, London. Sir William is distinguished by his fundamental work in x-ray crystal analysis. He has shown how to reveal the constitution of crystalline forms and accurately measure them, and his studies have given birth to a new tool which is bringing to light important facts regarding such complex structures as the larger organic molecules. Dr. Frank B. Jewett, chairman of the Committee on the Carty Fund, stated the reasons for the award, and Dr. A. H. Compton, of the University of Chicago, spoke on Sir William's work.

★

The John L. Lewis Prize of the American Philosophical Society has been conferred on Dr. Henry Norris Russell, Professor of Astronomy and Director of the observatory at Princeton University, "in appreciation of his contribution on 'stellar energy,' at the society's symposium on astrophysics in February." The presentation was made by Dr. Harlow Shapley, director of the Harvard College Observatory, at the annual dinner of the Society on April 22. Dr. Roland S. Morris, formerly United States Ambassador to Japan and president of the Society, presided. The speakers included Dr. Vannevar Bush, President of the Carnegie Institution of Washington; Dr. Victor G. Heiser, of the International Leprosy Commission, and Professor Jesse S. Reeves, of the University of Michigan.

★

The sixth award of the Edward Goodrich Acheson Medal and the $1000 prize of the Electrochemical Society was presented at the Columbus meeting on April 26 to Dr. Francis Cowles Frary, Director of the Research Laboratory of the Aluminum Company of America and known for his achievements in the metallurgy of aluminum. Previous recipients of the award are: Dr. Edward Goodrich Acheson, for his work on artificial graphite; Dr. Edwin F. Northrup, for the invention of the high frequency electric furnace; Dr. Colin G. Fink, for his contributions to electrochemistry; Dr. Frank J. Tone, for his work on carborundum, and Dr. Frederick M. Becket, for his contributions to electrometallurgy.

★

Conference on Spectroscopy

George Eastman Laboratories of Physics
Massachusetts Institute of Technology

Tentative Program of Papers

Monday, July 17, 9:30 A.M.: *Spectroscopic Analysis of Materials.*

W. F. MEGGERS, *National Bureau of Standards.*—**A Quarter Century of Spectrochemical Analysis at the National Bureau of Standards.**
C. C. KITCHIE, *Bausch & Lomb Optical Company.*—**An Alphabet of Modern Spectroscopy.**
E. K. JAYCOX, *Bell Telephone Laboratories (With A. E. Ruehle).*—**Quantitative Spectrochemical Analysis of Alloys, Solutions and Powders.**
A. MANKOWICH, *U. S. Naval Torpedo Station.*—**Spectrographic Analysis at the U. S. Naval Torpedo Station.**
H. C. HARRISON, *New York State College of Ceramics.*—**Some Applications of Spectroscopy to Ceramic Problems.**

Monday, July 17, 2 P.M.: *Spectrographic Apparatus.*

H. B. VINCENT, *University of Michigan (With R. A. Sawyer).*—**The Spectrographic Installation at The Ford Motor Co. (Illustrated with motion pictures.)**
R. C. MACHLER, *Leeds & Northrup Company.*—**A New Recording Microphotometer.**
W. A. KERR, *Carl Zeiss, Inc.*—**A New Rapid Spectrum Line Photometer.**
M. SLAVIN, *U. S. Department of the Interior.*—**Prism *Versus* Grating for Spectrochemical Analysis.**
G. R. HARRISON, *Massachusetts Institute of Technology.*—**Testing and Use of Concave Diffraction Gratings.**

Tuesday, July 18, 9:30 A.M.: *Spectrographic Methods of Analysis.*

B. F. SCRIBNER, *National Bureau of Standards.*—**The Comparison of Spectral Line Intensities Without a Plate Calibration Curve.**
W. R. BRODE, *Ohio State University.*—**The Influence of Extraneous Elements Upon the Intensity Ratio of Line Pairs Used in Quantitative Analysis.**
R. A. SAWYER, *University of Michigan (With R. W. Waggoner and A. A. Erickson).*—**Statistical Study of Lead in Human Blood and Urine.**
T. M. HESS, *Dow Chemical Company (With J. S. Owens and L. G. Reinhardt).*—**Analysis of Organic Material for Traces of Metallic Impurities.**
W. F. MEGGERS, *National Bureau of Standards.*—**Some Spectroscopic Suggestions.**

Tuesday, July 18, 2 P.M.: *Spectroscopy in Biology and Medicine.*

G. I. LAVIN, *Rockefeller Institute for Medical Research.*—**Applications of Ultraviolet Spectroscopy to Biochemistry and Medicine.**
G. O. LANGSTROTH, *Massachusetts Institute of Technology.*—**Spectrochemical Studies of Certain of the Male Hormones.**
D. L. DRABKIN, *University of Pennsylvania.*—**Spectrophotometric Studies Upon Hemoglobin and Derivatives. (a) Intracellular Hemoglobin. (b) Reaction of Cyanide with Ferrihemochromogens. (c) Kinetics of Protein Denaturation.**
ELEANOR M. KAPP, *Columbia University.*—**Spectrographic Observations on Urinary Porphyrins.**

Tuesday Evening: *Informal Dinner.*

Wednesday, July 19, 9:30 A.M.: *Emission and Absorption Spectroscopy.*

J. SCHUCH, *Harry W. Dietert Company.*—**Pulsating D.C. Arc Discharges.**
E. H. MELVIN, *National Bureau of Standards.*—**Quantitative Spectroscopic Analysis of Important Trace Elements in Commercial Mixed Fertilizers.**
J. S. OWENS, *Dow Chemical Company.*—**An Internal Control Method of Quantitative Absorption Spectrophotometry.**
A. E. RUEHLE, *Bell Telephone Laboratories (With E. K. Jaycox).*—**Use of the Spectrograph and Densitometer for Spectrophotometry and Colorimetry.**
D. L. DRABKIN, *University of Pennsylvania.*—**A New Type of Photoelectric Spectrophotometer.**

Wednesday, July 19, 2:00 P.M.: *General Spectroscopy and Discussion.*

L. W. STROCK, *Simon Baruch Research Institute.*—**Fundamental Features of the Photographic Process and Their Special Manifestation in Quantitative Spectrochemical Methods.**
EMMA P. CARR, *Mount Holyoke College.*—**The Ultraviolet Absorption Spectra of Simple Hydrocarbons.**
H. G. HOWELL, *University College.*—**Molecular Bands in Stellar Sources.**

General Discussion of the present status of spectroscopic analysis of materials, of absorption spectrophotometry, and of general questions raised by the papers of the conference.

Southeastern Section of the American Physical Society

The fifth annual meeting of the Southeastern Section of the American Physical Society was held at the University of Georgia, in Athens, on March 31 and April 1, 1939. The program consisted of over fifty papers, including a symposium on biophysics, at which a paper on "The Physical Basis of Biological Organization" was presented by Dr. Detlev W. Bronk, Director of the Johnson Foundation for Medical Research, who was a guest of the Section. Approxi-

mately 150 members and guests were registered at the meeting. The next annual meeting, in 1940, will be held in Charleston, S. C., upon the invitation of The Citadel. Officers of the Section, elected for the year 1939–40, are:

Chairman: B. A. Wooten, University of Alabama.
Vice Chairman: R. C. Williamson, University of Florida.
Secretary: Philip Rudnick, Vanderbilt University.
Treasurer: W. S. Nelms, Emory University.
Member of Executive Committee (four-year term): N. F. Smith, The Citadel.

★

The meetings of the AAAS, the APS and the AAPT which were held at Stanford University from June 26 to July 1 included symposia in three borderline fields of physics: astrophysics, high frequency electromagnetic waves, and structure determination by x-rays.

★

Iowa State College Press Established

A new publication outlet for manuscripts dealing with science and technology has been provided at Iowa State College, Ames, Iowa, by the recent organization of the Iowa State College Press. The major purpose of the new Press, as outlined in its statement of editorial policy, is "to serve learning, and particularly learning in fields of science and technology, by providing a channel of publication." The new press will consider for publication manuscripts, not from Iowa State College alone, but from any source. It will be especially interested in developing publications in certain subject matter fields in science and technology for which satisfactory publication channels are not elsewhere available.

★

ASTM Standards

Important modifications are to be made, according to an announcement from the Headquarters of the American Society for Testing Materials, in the methods of publishing the Society's standard specifications and tests. These changes are to become effective November, 1939. The major change is to combine the *Book of Standards* (issued triennially) and the *Book of Tentative Standards* (issued annually). These changes which also embody numerous advantages are necessary because of the great growth of ASTM standardization work.

All of the 870 ASTM standards are in widespread use in many branches of industry and commerce. Each is available, and will continue to be, in separate pamphlet form, and the standards have been issued in triennially published books of standards with an annual volume giving the so-called tentative standards and tests.

The new method of publication will be to issue the standards and tentative standards collectively in one triennial publication, divided into three parts: Part I, Metals; Part II, Non-Metallic Materials—Constructional; and Part III, Non-Metallic Materials—General. Publication of new and revised tentative standards in the annual *Proceedings*, Part I, will be discontinued; the *Proceedings* including both committee reports and papers (about 1300 pages double-column format) will be bound in one volume. The publication of the annual *Book of Tentative Standards* will be discontinued entirely. (The November, 1938, edition is thus the last one to be issued.)

In the two years between triennial publication of the new book, supplements to each of the three parts will be issued, containing revisions and new or revised standards and tentative standards for that year. Since these books will be appreciably larger than the present supplements and will have permanent reference value, they will be bound in cloth. The volume on *Methods of Chemical Analysis of Metals*, published in 1936, will be continued as a separate publication.

★

New Sigma Pi Sigma Chapter

On May 22, at Wayne University, Detroit, Michigan, Sigma Pi Sigma, physics honor society, installed its thirty-third chapter. The installing party consisted of Dr. F. C. Blake, national president, of Ohio State University, Dr. M. W. White, executive secretary, of Pennsylvania State College, and Dr. C. W. Chapman of Michigan State College. At an open meeting after the installation banquet Dr. P. E. Klopsteg gave an illustrated lecture on "Scientific Aspects of Archery."

★

Calendar of Meetings

July	
6–8	Sixteenth Colloid Symposium, Stanford University, Cal.
10–14	American Society of Mechanical Engineers, San Francisco, Cal.
10–13	American Institute of Mining and Metallurgical Engineers, San Francisco, Cal.
September	
4–12	International Congress of Mathematicians, Cambridge, Mass.
4–15	International Union of Geodesy and Geophysics, Washington, D. C.
11–15	American Chemical Society, Boston, Mass.
20–23	Institute of Radio Engineers, New York, N. Y.
October	
5–7	American Institute of Mining and Metallurgical Engineers, Coal Division, Columbus, Ohio.
12–14	Optical Society of America, Lake Placid, N. Y.
23–25	American Institute of Mining and Metallurgical Engineers, Metals Division, Chicago, Ill.
23–27	American Society for Metals, Chicago, Ill.
November	
2	U. S. Institute for Textile Research, New York, N. Y.
3–4	Acoustical Society of America, Iowa City, Iowa.
2–4	American Institute of Mining and Metallurgical Engineers, Industrial Minerals Division, Tuscaloosa, Ala.
15–17	American Institute of Chemical Engineers, Providence, R. I.
December	
1–2	American Physical Society, Chicago, Ill.
27–Jan. 2	American Association for the Advancement of Science, Columbus, Ohio.
28–30	American Physical Society, Columbus, Ohio.
28–30	Geological Society of America, Minneapolis, Minn.

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Necrology

Philip E. Bliss, President of the Warner and Swasey Company, Cleveland, manufacturers of astronomical instruments and machine tools, died on April 11 at the age of fifty-three years.

Contributed Original Research

Cathode-Ray Bunching

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(Received January 20, 1939)

The bunching of cathode rays in the klystron, described in this Journal by R. H. Varian and S. F. Varian, is treated mathematically here, and is found to result in a current having a wave form with sharp peaks and containing strong higher harmonics. In the absence of appreciable "de-bunching" by mutual repulsion, the kinematics of the bunching process leads to specifications for an optimum condition of bunching and to the prediction of an ideal efficiency of 58 percent for the conversion of the cathode-ray power into high frequency power. De-bunching becomes important under certain calculated conditions, limiting the amplification factors obtainable in amplifiers without regeneration. It also changes the optimum conditions for oscillators and reduces their efficiencies by calculable amounts. The power required in the buncher is relatively very small and depends on the buncher voltage almost like that of an additional ohmic resistance.

I. INTRODUCTION

THE purpose of this paper is to report a mathematical investigation of the bunching of cathode rays in the Varian[1] brothers' amplifier or oscillator now called the "klystron."

In this apparatus, as reported more fully in the above reference, cathode rays of uniform speed enter a Hansen[2] resonator, or "rhumbatron," going along the lines of its electric field. They emerge at slightly different speeds, depending on the strengths and directions of the field during their passage through the rhumbatron. Then they make a relatively long flight in a space free from any fields of rhumbatron frequencies, though not necessarily free from d.c. focusing fields or relatively low frequency fields used for modulation of signals. In this space, the differences in their speeds cause them to collect into bunches, in a way described qualitatively by the Varian brothers. Since these bunches pass any fixed point with a frequency equal to that of the oscillations in the rhumbatron just mentioned, though with a wave form far from sinusoidal, they can be sent through another rhumbatron and made to deliver power to it, either at that frequency or a multiple of it. The former of these rhumbatrons is called the "buncher," and the latter the "catcher," the space between them is the "bunching space" and the apparatus as a whole is a "klystron." If the buncher is driven by an external source of power, the klystron is an amplifier; but if the buncher is driven by power transmitted from the catcher, the klystron is an oscillator.

In either case, the klystron converts part of the d.c. power fed to its electron gun (or cathode and first grid at the potential of the rhumbatrons) into a.c. power which appears in the catcher. In any klystron, a part of this a.c. power is lost in ohmic resistance in the catcher; and in an oscillator a part is transmitted to the buncher; the rest is available for other uses. While it is important to know what fraction is thus available, a more fundamental problem is the one treated here, namely that of the efficiency of conversion of the d.c. power into a.c. power in the catcher.

This problem will be treated in two degrees of approximation: first, as what may be called purely kinematic bunching, where the cathode rays are assumed to cross the bunching space at the speeds given them by the gun and buncher, without further acceleration until they reach the

[1] R. H. Varian and S. F. Varian, J. App. Phys. **10**, 321 (1939).
[2] W. W. Hansen, J. App. Phys. **9**, 654 (1938).

catcher; and second, where each partially formed bunch in the bunching space exerts electrostatic forces on the electrons in its own front and back, tending to change their speeds so as to impair the bunching, or to "de-bunch" them.

Finally, there will be a brief treatment of a subordinate problem, that of how much power is required to drive the buncher, over and above its ohmic losses, because of its having to bunch the cathode rays. This problem is subordinate because this power is relatively low.

II. Purely Kinematic Bunching: The Wave Form of the Current

For simplicity, it will be assumed here that all the cathode rays and electric fields are exactly parallel to the axis of the klystron and that the electric fields are bounded by grids so good as to be equivalent to mathematical discontinuities in the fields. These assumptions involve the neglect of any loss of cathode rays between the buncher and catcher because of either poor aim or space-charge repulsion or impact on the grids; also they involve the neglect of any focusing fields, in case the cathode rays are focused through holes instead of grids, and of any low frequency fields introduced for modulation. These factors may greatly modify the results quantitatively, but not qualitatively; and the losses of cathode rays are allowed for if the currents at the cathode and the buncher, as mentioned in the equations, are by definition only currents carried by such electrons as will later pass through the catcher. Other electrons are of no concern here, except in the problem of the power required to drive the buncher.

With this understanding, the notation will follow these rules: Capital V's refer to line integrals of electric fields; lower-case v's to speeds; i's to currents; s's to distances; subscripts 0, 1 and 2, respectively, to the electron gun, the buncher, and the catcher, as shown in Fig. 1.

Since the rhumbatrons are at the same d.c. potential and are often grounded, for safety in handling, that potential will be taken as zero. The cathode is then at a potential V_0, negative of course; so if e stands for the charge of an electron, also negative, eV_0 is positive and

$$eV_0 = mv_0^2/2, \tag{1}$$

where m is the mass of an electron and v_0 its speed at the first grid.

Letting ω stand for 2π times the frequency at which the klystron is running, and measuring time from an appropriate zero, the speed of any electron passing the middle of the buncher at time t_1 may be called approximately

$$v_0 + v_1 \sin \omega t_1. \tag{2}$$

More exactly, the line integral of the electric field through the buncher (which is not simply a difference of scalar potentials, but involves vector potentials also) may be called

$$V_1 \sin \omega t_1, \tag{3}$$

but in practical cases v_1 is small enough, relative to v_0, and the time of transit through the buncher is small enough, relative to the period of oscillation, so that (2) is satisfactory except in the

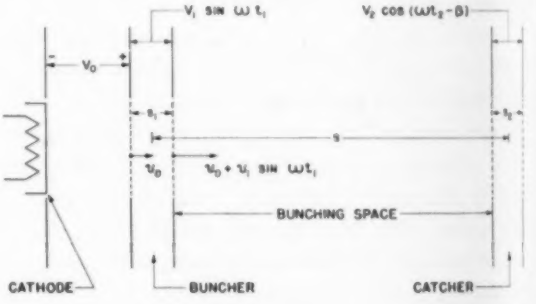

FIG. 1.

theory of the power required for bunching, treated in the last section of this paper. Using these approximations again,

$$mv_0v_1 = eV_1. \tag{4}$$

Letting t_2 stand for the time at which this electron passes the middle of the catcher,

$$t_2 = t_1 + \frac{s}{v_0 + v_1 \sin \omega t_1}, \tag{5}$$

or approximately

$$t_2 = t_1 + \frac{s}{v_0} - \frac{sv_1}{v_0^2} \sin \omega t_1. \tag{6}$$

Letting

$$\theta = \omega t_1 \tag{7}$$

and

$$x = \omega t_2 - \frac{s\omega}{v_0} \tag{8}$$

and

$$r = \frac{s\omega v_1}{{v_0}^2}, \tag{9}$$

$$x = \theta - r \sin \theta, \tag{10}$$

a form reminiscent of the theory of trochoids. Letting i_0, i_1 and i_2 stand for instantaneous currents as indicated by their subscripts, and using parentheses for functional relationships as usual, the law of conservation of charge requires that

$$i_1(t_1)dt_1 = i_2(t_2)dt_2. \tag{11}$$

Since i_1 is practically equal to i_0 at all times, it follows that

$$i_2 = i_0/y, \tag{12}$$

where

$$y = 1 - r \cos \theta, \tag{13}$$

and this is the other equation of the trochoid to match Eq. (10).

The trochoid described by Eqs. (10) and (13) has a rolling circle of unit radius, with a tracing point at a radius r from its center.

When $r \ll 1$, therefore, this trochoid is very nearly sinusoidal about the horizontal line $y=1$; and the curve for its reciprocal, which is the wave form of the cathode-ray current, is also nearly sinusoidal. As r increases, however, the trochoid approaches a cycloid and the current wave acquires a high, sharp crest,* which becomes infinitely high and sharp when $r=1$, though of course having only a finite area. When $r>1$, the trochoid is looped, cutting the x axis twice in each period, and the current wave has two peaks. These changes are illustrated in Fig. 2.

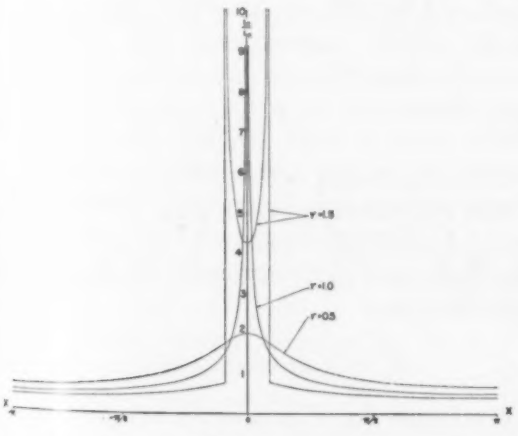

FIG. 2.

III. Purely Kinematic Bunching: Harmonics and Power

A wave form such as this is obviously rich in high harmonics, and suggests the possibility of profitable frequency multiplication by passage of these cathode rays through a catcher of appropriate resonant frequency, as anticipated by the Varian brothers. Expressing i_2 as a Fourier series, the integrals giving the coefficients turn out to have forms fundamental to the theory of Bessel's functions, in terms of which,

$$i_2(x) = i_0[1 + 2\{J_1(r)\cos x + J_2(2r)\cos 2x + \cdots + J_n(nr)\cos nx + \cdots\}]. \tag{14}$$

When $r<1$, this series may be proved convergent at all values of x; when $r=1$ it converges except at $x=0$ or a multiple of π, where its nth term approaches $0.4473n^{-\frac{1}{3}}$ when n is large; when $r>1$ it converges at all points except those at which the trochoid crosses the axis, where the nth term approaches

$$\{4\pi(r^2-1)^{\frac{1}{2}}n\}^{-\frac{1}{2}} \tag{15}$$

after n has become so great as to make this expression $\ll 1$.

In finding the power caught by the catcher, it will be assumed for generality that the catcher oscillates at a frequency n times that of the buncher, where n is any integer. To allow for phase changes, the line integral of its electric field at time t_2 will be called

$$V_2 \cos(nx - \beta) \tag{16}$$

with positive values denoting retarding fields and

* *Note added in proof.*—This crest is essentially the same as the "phase focusing" predicted by E. Brüche and A. Recknagel, Zeits. f. Physik **108**, 459 (1938), for electrons passing through fields changing linearly with time. They found that it should be possible to focus electrons to a single, infinitely narrow bunch, by making the field a certain nonlinear and nonsinusoidal function of time.

β arbitrary. Then the power taken from the cathode rays averages over their whole cycle to the value

$$P_2 = i_0 V_2 J_n(nr) \cos \beta. \tag{17}$$

Since the d.c. power given to these cathode rays is

$$P_0 = i_0 V_0, \tag{18}$$

the efficiency of the conversion of power from d.c. to a.c. is

$$E_2 = (V_2/V_0) J_n(nr) \cos \beta. \tag{19}$$

To increase the efficiency, therefore, one must increase each factor in (19) to its maximum. The simplest is $\cos \beta$. In increasing (V_2/V_0), the validity of these equations is limited by the tacit assumption that all cathode rays entering the catcher succeed in passing through it. This can be true only if, for every time

$$V_2 \cos (nx - \beta) < V_0 + V_1 \sin \theta, \tag{20}$$

or practically, since $V_1 \ll V_0$, if $V_2 < V_0$. Otherwise, not only do these equations fail to hold, but also the catcher throws some of the cathode rays backward and in so doing throws away their power. For an ideal case, therefore, V_1 may be neglected and V_2 set equal to V_0, when

$$E_2 = J_n(nr). \tag{21}$$

Some values of $J_n(nr)$ are plotted against r in Fig. 3.

In most cases, especially in the simple klystron oscillator, $n=1$. Then the maximum possible efficiency occurs at $r=1.84$. Here $J_1(r)=0.582$, giving an ideal efficiency of 58 percent, and the bunching has been carried so far that the two peaks in the current wave of Fig. 2 are 63 electrical degrees apart.

An interesting experimental confirmation of the existence of such pairs of peaks is furnished by the velocity spectra described by the Varian[1] brothers. If $\beta=0$, these peaks pass the catcher at times equally far before and after the peak of its retarding voltage; but if β is made much different from zero the electrons in the peaks encounter different retardations and so make two bright spots in the velocity spectrum. The peaks have been seen in this way in numerous tests by S. F. Varian and the author: not in every spectrum, but apparently occurring whenever r is great enough; and by varying β the bright spots can often be made to move in opposite directions along the spectrum and to pass one another, in the manner predicted by these equations.

The negative values of P_2 and E_2 predicted by Fig. 3 with excessive values of r (greater than 3.83 if $n=1$) are likewise explained by the positions of the peaks in the current wave, since

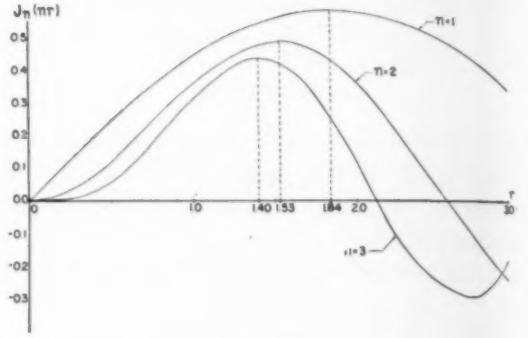

FIG. 3.

they spread apart out of the retarding half-cycle of the catcher voltage and into times of forward acceleration. Such values of r, therefore, are usually to be avoided.

Below 1.84, on the other hand, r can be reduced considerably and still maintain almost ideal efficiency. So, in practice, to save power in the buncher, it is usually best to run an oscillator with r in the region between 1 and 1.84.

Turning to frequency multipliers, it appears from Fig. 3 that as n is increased one must keep nearer to the optimum r, which is, itself, somewhat less than with $n=1$. These facts are readily explained by the necessity for keeping the two peaks of the current wave well within one retarding half-cycle of the catcher voltage. The best values of r, for $n=2$, 3, 8 and 16, respectively, are 1.53, 1.40, 1.22 and 1.13, with $J_n(nr)$ having the values 0.487, 0.434, 0.32 and 0.26. These, perhaps surprisingly high, ideal efficiencies might be difficult to approach in practice, but they indicate interesting possibilities in frequency multiplication.

IV. De-bunching Forces

One cause for difficulty in approaching the ideal efficiencies just described is undoubtedly

the "de-bunching" effect of space-charge repulsions, as noted in Section I. This effect must now be calculated.

There are two practical conditions tending especially to introduce de-bunching. One occurs in an amplifier. Here, with a weak signal, v_1 is very small and Eq. (17) tempts the designer to try to increase r toward its high power range by greatly increasing s. This gives the de-bunching forces a long time in which to act. The other condition promoting their action is high current density, as found in a large, high power oscillator.

In the former of these cases, any one electron on its way through the bunching space is surrounded by waves of space charge in which the change of amplitude from one wave to the next is so slight that the problem of calculating the de-bunching forces can be simplified without much loss of accuracy by neglecting that change. In the latter case, this simplification may result in a rougher approximation, but on account of other complications this may be still the best method.

Since the forces of interest here are only those caused by the excesses and deficiencies of space charge with respect to its average value, or its value in the absence of oscillations, the problem will be treated as though this average value was just canceled by a space charge of stationary positive ions (as indeed it may be in some cases). The width of the beam will be considered to be infinite, thereby greatly simplifying the calculation but making the calculated de-bunching forces exceed the real ones.

The excess of the charge density at any point over its average value is then

$$\rho=\rho' \cos k_0 z+\rho'' \cos 2k_0 z+\cdots, \tag{22}$$

where

$$k_0=\omega/v_0 \tag{23}$$

and z is the distance of this point from the crest of the nearest bunch of electrons, and ρ', ρ'' etc. are the coefficients of the various harmonics. From this, by Poisson's equation and one integration using electrostatic units, the de-bunching electric field is found to be

$$-D_z V=+(4\pi/k_0)(\rho' \sin k_0 z + (\rho''/2) \sin 2k_0 z+\cdots). \tag{24}$$

V. De-bunching in a Long Amplifier

In an amplifier receiving a weak signal, as noted in the preceding section, r is always small; and even with stronger signals the condition for linearity of amplification is that r must be small enough to justify the approximation

$$J_1(r)=r/2. \tag{25}$$

Under these conditions, the higher harmonics in all these equations may be neglected. Thus the last terms of Eqs. (22) and (24) are dropped; and Eq. (14), which applies only in the absence of appreciable de-bunching, becomes

$$i_2(x)=i_0[1+r \cos x]. \tag{26}$$

Since the de-bunching forces act on electrons, all the way along the bunching space, the calculation of their effect consists in setting up a differential equation in terms of distance from the buncher, to be called s', solving it with known initial conditions at $s'=0$, and finally applying the solution to the catcher, where $s'=s$.

For this purpose, the oscillations in the buncher will be assumed to be as in Eqs. (2), (3) and (4); and at any time t', in analogy with (8) and (9), x', r' and k_1 will be defined by

$$x'=\omega t'-k_0 s' \tag{27}$$

and

$$r'=\frac{s'\omega v_1}{v_0^2}=k_0 s'\frac{v_1}{v_0}=k_1 s'. \tag{28}$$

The current at position s' and time t' will then be called $i'(x')$, and by analogy with Eq. (26), u' will be defined by

$$i'(x')=i_0[1+u' \cos x']. \tag{29}$$

The differential-equation problem outlined above then resolves itself into one of finding u' as a function of s' with the initial conditions:

$$\text{at } s'=0, \quad u'=0; \tag{30}$$

and

$$\text{at } s'=0, \quad \frac{du'}{ds'}=\frac{dr'}{ds'}=k_1. \tag{31}$$

To find the differential equation itself, remembering that $r\ll 1$ and so that r' and u' are even smaller, it is evident that in the absence of

de-bunching forces any electron at a distance z ahead of the center of a bunch can be expected to be falling back toward that center at a relative speed $v_1 \sin k_0 z$. With de-bunching forces as given by the first term of Eq. (24), using electrostatic units again, the reduction in this relative speed during any time dt' is found to be

$$4\pi \frac{e\rho'}{mk_0} \sin k_0 z dt'. \tag{32}$$

This changes du'/dt' and therefore also du'/ds' by amounts bearing the same ratio to their initial values which expression (32) bears to $v_1 \sin k_0 z$; so the reduction in du'/ds' is

$$4\pi \frac{e\rho'}{mv_0} dt'. \tag{33}$$

In this time, the bunch advances a distance $v_0 dt'$, and therefore

$$\frac{d^2u'}{ds'^2} = -4\pi \frac{e\rho'}{mv_0^2}. \tag{34}$$

ρ' is related to i' by the fact that the average current i_0 is carried by cathode rays of average speed v_0. Letting A stand for the cross-sectional area of the beam, and ρ_0 for the average density,

$$i_0 = Av_0\rho_0. \tag{35}$$

Therefore

$$\rho' = \rho_0 u' = i_0 u'/Av_0, \tag{36}$$

and the final differential equation for u' is

$$\frac{d^2u'}{ds'^2} = -4\pi \frac{ei_0}{mv_0^3 A} u' = -h^2 u', \tag{37}$$

defining a new radian wave number h. In calculating h, it must be carefully remembered that the e and i_0 of this definition are constrained by Eqs. (24) and (32) to be in electrostatic units; and that since e is negative, so is i_0.

Since these three radian wave numbers, k_0, k_1 and h, are easily confused, the wave-lengths associated with them are specified here as follows: With k_0 is the distance between successive bunches; with k_1 is the distance between successive places where a catcher could be located to produce positive maxima in the power calculated in Eq. (17), that is, in $J_1(r)$, which is $J_1(k_1 s)$, when s is made so great as to have already reversed the sign of $J_1(k_1 s)$ a few times; with h is the distance a bunch would have to travel to make space-charge repulsion alone reduce it to a "hollow" and then reconstruct it as a bunch. Needless to say, in practice one usually cannot expect to have even one complete wave for either k_1 or h, but only to have a moderate fraction of a wave; and the first half-wave of a Bessel function is considerably longer than later half-waves. These parts of first waves associated with k_1 and h are fixed in space, while the bunches, of relatively short wave-length associated with k_0, move through them with speed v_0.

The solution of Eq. (37) with initial conditions (30) and (31) is clearly

$$u' = (k_1/h) \sin hs'. \tag{38}$$

So for the current at the catcher, Eq. (26) is replaced by

$$\begin{aligned} i_2(x) &= i_0[1 + u \cos x] \\ &= i_0[1 + (k_1/h) \sin hs \cos x]. \end{aligned} \tag{39}$$

When hs is very small, this approaches (26) as it should. This is the usual case. For example, if the beam carries 10 ma in an area of 1 sq. cm, with the cathode at -2550 volts so that $v_0 = 3 \times 10^9$ cm/sec. and s is 10 cm, hs is only about 0.086. But if an attempt were made to increase the amplification greatly by making the length many meters, one would have to stop at about two meters, with this cross section and current, because of de-bunching.

VI. De-bunching in High Power Oscillators

Another case where de-bunching may be important, as noted in Section IV, is in a high power oscillator, especially one of a low frequency, where the beam must be longer than at higher frequencies. In this connection it is especially significant that the frequency does not occur in the definition of h, Eq. (37), either explicitly or through k_0, the radian wave number of the bunches. So de-bunching does not limit the number of bunches a beam may contain, but limits its length.

To calculate its effect when r is too large for the approximation $J_1(r)\rightarrow r/2$, use may be made of the fact that the reduction in the relative speeds involved in bunching, during the time dt', as calculated in the preceding section, is equivalent to the passage of the beam through a second buncher, working at an infinitesimal voltage and in phase opposite to the first. So writing Eq. (14) in the form

$$u=2J_1(k_1s) \tag{40}$$

as a first approximation, a second approximation can be written as this u plus the sum of the negative du's contributed by all these fictitious infinitesimal bunchers. Since any one such buncher has the greatest effect if it lies about halfway along the bunching space, the departure from linearity in what corresponds to $J_1(r)$ for all of them together must be less than a quarter as great, relatively, as for the real buncher. For practical purposes, then, in the range of r actually used, a fair approximation is

$$u=2J_1(k_1s)-\int_0^s h^2k_1s'(s-s')ds', \tag{41}$$

or nearly as accurately,

$$u=k_1s\{1-(k_1^2s^2/8)-(h^2s^2/6)+\cdots\}, \tag{42}$$

or in an approximation suggested by its reduction to Eq. (39) when $k_1s\ll 1$,

$$u=2J_1(k_1s)\frac{\sin hs}{hs}. \tag{43}$$

Approximation (42) evidently always underestimates u, while (43) overestimates it; but neither is in error by more than about five percent at any value of s up to that which makes u its maximum.

From either of these approximations, it is evident that so long as $h\ll k_1$, de-bunching may be neglected, and the bunching may be treated as purely kinematic; when h and k_1 are of the same order of magnitude, both tend to limit the power of the oscillator, and the optimum value of s is less than if the bunching was purely kinematic; and when $h\gg k_1$, the kinematic limitations may be neglected in comparison with those imposed by de-bunching.

VII. Power Required for Bunching

While the power required in the buncher, because of the cathode rays it must bunch, is almost obviously too small to be included in a general accounting of the power conversion in the klystron, at least until the major items are calculated more exactly, it is of importance in the design of the circuit by which it must be supplied to the buncher.

This power P_1 is small, in comparison with P_2, for two reasons. First, since $V_1\ll V_2$, even when $V_2\rightarrow V_0$, the energy given to electrons by the buncher during the half-cycle in which their speed is increased is small in comparison with that taken from them by the catcher. And second, the buncher is almost repaid for this energy by the electrons in the next half-cycle, which lose speed. Indeed the difference between these expenditures and repayments is so much smaller than either alone as to require considerable care in any approximate calculation, not to use an approximation with errors which might integrate over the cycle to something of the same order.

In calculating P_1, therefore, the gain of kinetic energy by any electron must be expressed as a function of the time at which it passed the first grid, where the number of electrons per unit time is strictly constant (thereby abandoning an approximation made in Eq. (12) and satisfactory up to this point), and then this must be multiplied by the number of electrons in time dt and integrated over the cycle. For this integration, it is convenient to expand several functions of time by Taylor's series for each electron, covering its transit time, and the precaution against errors discussed above consists primarily in keeping the quadratic terms in these series.

The result is

$$P_1=\frac{i_0V_1^2}{32V_0}\left\{\left(\frac{s_1\omega}{v_0}\right)^2+\frac{3}{32}\left(\frac{V_1}{V_0}\right)^2\right\}, \tag{44}$$

where s_1 is the distance between the grids of the buncher, as defined in Fig. 1.

In practice the second of these terms is usually very much smaller than the first, so that P_1 is nearly proportional to V_1^2. Thus it changes with V_1 in almost the same way as would the loss due

to a moderate increase in the ohmic resistance of the buncher.

To reduce this loss as far as possible, obviously the klystron should be designed for high cathode voltage and low current, and s_1 should be as small as is convenient.

VIII. Summary

In conclusion, the chief results of these calculations may be summarized as follows.

1. Whenever $h \ll k_1$ the bunching is purely kinematic, and the ideal efficiency is 58 percent.

2. To approach this ideal, the catcher must oscillate in the proper phase and with a peak voltage nearly equal to the d.c. voltage of the cathode, and the relation between the various parameters of the klystron must be such that $s\omega v_1/v_0^2$ is fairly near 1.84, though efficiencies reasonably near the ideal can be approached as well with a fairly wide departure from this value.

3. The wave form of the current is sharply peaked, and so has strong higher harmonics which may prove useful in frequency multipliers.

4. De-bunching by mutual repulsion sets a limit to the gain in an amplifier, and so to the amplification that can be obtained with a given beam without regeneration; and it is also a serious factor in any oscillators with long beams of dense cathode rays, such as are indicated for high power at relatively low frequencies.

5. The power required in the buncher for its work on the cathode rays is relatively very low and behaves nearly like that of a certain calculable increase in its ohmic resistance.

Ionic Mobility in Solid Dielectrics

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(Received January 4, 1939)

1. It is assumed that ionic mobility in solid dielectrics is controlled by a combined resistance of viscosity, elasticity and solid friction.

2. Under this assumption ionic mobility under alternating electric stress is calculated. It appears from the formulae that there is a finite contribution due to ions toward both the dielectric constant and loss factor. In the range of technical and acoustical frequencies both are in first approximation independent of frequency. The loss factor, controlled by the solid friction, is equivalent to an a.c. conductivity several orders higher than the d.c. conductivity, as known from observation.

3. Applying the same conception to ionic mobility in a constant field of high intensity, it appears that ions cover only part of their travel by a viscous flow, a small fraction being due to elastic displacements. This latter increases with the field strength. The energy stored during this displacement is finally converted into vibratory kinetic energy of the ion, thus enabling it to accumulate energy and finally ionize. The theory shows that this process becomes appreciable at a field strength between 10^4 and 10^5 v/cm in agreement with observations on the increase with field strength of the conductivity.

I

In some recent publications[1] the author has tried to incorporate solid friction into the theory of solid dielectrics. The principal idea is the following. A solid body, taken in its most general form, that is exhibiting a finite plasticity, will behave entirely differently if subjected to a steady or an alternating stress. In the first case its reaction is controlled mainly by its viscosity (plasticity), in the second by its elasticity plus solid friction. The three factors just mentioned are independent characteristic constants, having no direct connection with each other.

It is now possible to extrapolate this behavior to the elementary particles within the body which are responsible for its electrical properties. In the preceding publications this idea has been carried out with regard to rotation of dipolar molecules, and it has been shown that the results are in fair agreement with experimental observations on dielectric losses, part of which are due to dipolar rotations.

[1] A. Gemant: Trans. Faraday Soc. **31**, 1582 (1935); **34**, 269 (1938); J. App. Phys. **9**, 730 (1938).

It has been already mentioned in the papers quoted above that the theory could be extended to ions just as well. In case the general assumptions are correct, this application appears not only possible, but necessary. In the present paper an attempt shall be made to indicate the conclusions to which this application leads. In the first part of the paper ionic mobility, with alternating electric force, will be discussed.

There exists also a possibility of applying the theory to ionic mobility in a constant field of high intensity. Definite results are obtained from this point of view as well, and these will be dealt with in the second part of the paper.

The quantitative deductions can only be regarded as first approximations. Nevertheless, the results obtained seem to be interesting, and are, as will be shown, in good qualitative agreement with experimental results in both fields. Because of the fact that several mechanisms generally overlap in technical dielectrics, from which most of the results are obtained, a rigorous quantitative test by means of the existing data does not seem to be feasible.* But if special materials are selected for experimental purposes, in order possibly to eliminate (or minimize) other mechanisms than the one considered here, then a direct comparison with the theoretical conclusions will be made possible.

II

In applying the conception of solid friction to ions, one has to specify the resistance which has to be overcome during the motion of the ion. It is assumed that the ion, embedded in a solid dielectric, can be displaced in two different ways, just as the whole body can be deformed in two different ways. One of these ways is a viscous flow (corresponding to the plastic deformation of the body), the other an elastic displacement (corresponding to the elastic displacement of the body). By picturing this in a mechanical model, Fig. 1 is obtained which, by the way, is the reversed picture to that of an electrical model.[2] In this picture i represents the ion, and 1 is a kind of piston, allowing a viscous flow, controlled by the viscosity η_0. The elastic displacement of i is made possible by means of the spring 2, controlled by the shear modulus of elasticity μ. Any elastic displacement is accompanied by a solid friction-loss, represented by the element 3, and controlled by the so-called specific loss θ (ratio of energy loss per cycle to that of energy stored in the spring).

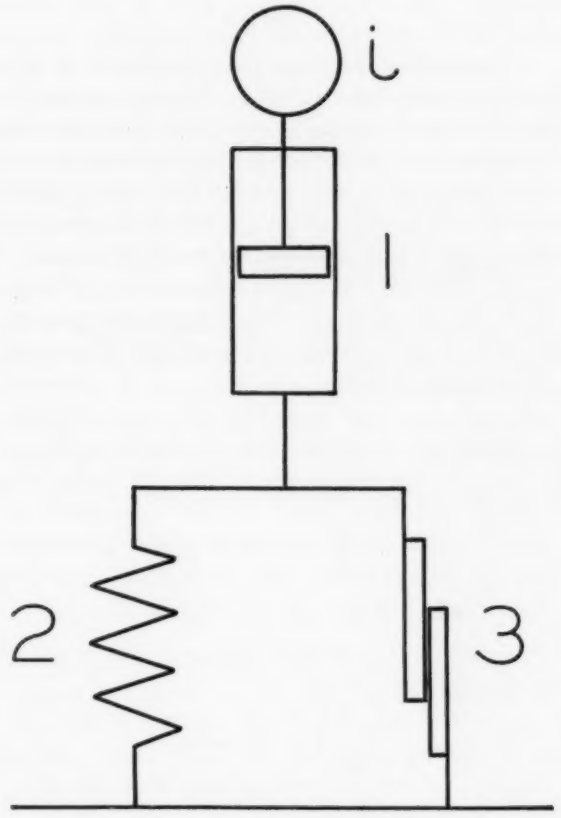

FIG. 1. Model of ionic resistance in a solid.

As to the actual physical processes, underlying the three elements η_0, μ and θ, a few remarks should suffice here. During a *viscous flow* of the ion the surroundings behave as a liquid, the path along which an ion had passed has not quite the same configuration as it had had before, the change becoming more pronounced with increasing plasticity. During an *elastic displacement*, on the other hand, the immediate neighborhood behaves as a crystal lattice, possessing a rigid configuration. As to the mechanism of the *solid friction*, it might have a thermodynamic origin, but in any case is very likely connected with the imperfections of the lattice.[3]

* Numerical computations on existing data are contained in another paper by the author, presented at the Society of Rheology meeting in Pittsburgh, December, 1938.

[2] See in this connection the interesting article by F. A. Firestone, J. App. Phys. **9**, 373 (1938).

[3] C. Zener, Phys. Rev. **53**, 90 (1938).

III

Considering now the ionic mobility at alternating voltage, we will disregard any mechanism due to dipolar constituents, as well as those due to inhomogeneities, and only assume the presence of n (univalent) ions per cc. The ionic mobility for d.c. is given by $e/\lambda\eta_0$, where e = electronic charge and λ is a length of molecular order of magnitude. This is a generalized form of Stokes' law with the numerical coefficient left open. The dielectric constant due to atomic (plus electronic) polarization should be ϵ_a.

In turning our attention to a.c., a complex conductivity σ^* can be written down; namely,

$$\sigma^* = ne^2/\lambda\eta^* + i\omega\epsilon_a/4\pi, \tag{1}$$

where $\omega = 2\pi$ times frequency of the alternating voltage, and η^* is the complex viscosity, resulting from the model Fig. 1. Writing for η^*

$$\eta^* = \eta' - i\mu'/\omega, \tag{2}$$

we have:[1]

$$\eta' = \eta_0 \frac{1+\tau_0(\eta/\mu)\omega^2}{1+\tau_0^2\omega^2}, \tag{3}$$

$$\mu' = \mu\tau_0^2\omega^2/(1+\tau_0^2\omega^2) \tag{4}$$

where τ_0 stands for η_0/μ, and η is a fictive quantity, the so-called "equivalent viscosity" of solid friction. It has only a meaning for alternating processes, and its advantage is in allowing Eq. (3) to be deduced by using the well-known equations of alternating-current theory. It has, however, to be replaced by θ by means of some empirical relation obtained experimentally.

Although not too many reliable data on dielectrics exist up to now, those obtained by Kimball,[4] Wegel and Walther,[5] and Gemant and Jackson,[6] are in agreement in indicating the relation

$$\eta = \mu\theta/2\pi\omega \tag{5}$$

as valid from lowest up to acoustical frequencies. There are, however, experimental results as those obtained by Bennewitz and Rötger[7] on glass, showing a different function. According to their result θ itself is not independent of frequency but is reduced to about its half-value in increasing the frequency from 1 to 100. This would mean an exponent for ω in (5) slightly higher than unity. However, Eq. (5) will be used in the following.

Equation (2) is now being substituted into (1). Writing (1) in the form

$$\sigma^* = \frac{ne^2}{\lambda\bar{\eta}} + i\frac{\omega\bar{\epsilon}}{4\pi}, \tag{6}$$

where $\bar{\eta}$ (now a real quantity) is the apparent viscosity for the frequency ω, and $\bar{\epsilon}$ the apparent dielectric constant, one obtains:

$$\bar{\eta} = \eta' + \mu'^2/\omega^2\eta', \tag{7}$$

$$\bar{\epsilon} = \epsilon_a + 4\pi k\mu'/(\mu'^2+\omega^2\eta'^2), \tag{8}$$

in writing

$$k = ne^2/\lambda. \tag{9}$$

The loss angle, tan δ, then becomes:

$$\tan\delta = 4\pi k/\omega\bar{\epsilon}\bar{\eta}. \tag{10}$$

These equations completely describe the behavior of such a dielectric in an alternating field.

IV

The next step is to insert numerical values into the equations in order to see the order of magnitude of the effect. Let us consider frequencies from 60 cycles up ($\omega > 400$). In the model Fig. 1 μ is of the order 10^{10} abs. units (the shear modulus of ebonite, for instance). θ is of the order 10^{-5}, according to the results quoted above.[4-6] There is some difficulty in fixing the value for η_0. Measurements of the macroscopic viscosity for glass at higher temperatures allow an extrapolation for room temperature, indicating the order 10^{15} poise. It is, however, quite uncertain, whether this is the right order for molecular processes as well. The following rough estimate shows that a lower order, about 10^{12}, seems more likely.

We write the d.c. conductivity proportional to n/η_0, and assume as rough approximation that the proportionality constant is the same both in liquids and solids. Considering further that the order of the d.c. conductivity at room temperature both in oils and technical insulating solids, is the same, namely, 10^{-14} mhos/cm, it

[4] A. L. Kimball, *Vibration Prevention in Engineering* (Wiley, New York, 1932), p. 133.
[5] R. L. Wegel and H. Walther, Physics **6**, 141 (1935).
[6] A. Gemant and W. Jackson, Phil. Mag. **23**, 960 (1937).
[7] K. Bennewitz and H. Rötger, Physik. Zeits. **37**, 578 (1936).

follows that the ratio n/η_0 is, as it happens, about the same in both cases. Now n in oils can be estimated[8, 9] to about 10^9 ions per cc; η_0 being of unity, the ratio is 10^9. Assuming the same ratio for insulating solids, we obtain the following Table I. The first column contains the value chosen for η_0, the second the value for n, as calculated from the above ratio. The total number of molecules per cc, n_m, being about 10^{22}, the third column contains the ratios n/n_m.

From the last column it can be concluded that whereas the order for η_0 of 10^{15} or 10^{14} does not appear to be possible, 10^{12} or 10^{11} seem to be more likely, anyhow as a maximum value. It should be emphasized, however, that the assumed order is only provisional and open to revision in the face of any future experimental evidence.

Inserting all these values into (3) and (4), one sees that for $\omega > 400$, η' becomes η, and μ' becomes μ. To be sure, for d.c. ($\omega = 0$) η' is η_0 and μ' zero, but, due to the large time constant, τ_0, they change over into their "high frequency" value at very low frequencies (about 0.1 cycles).

These values for η' and μ' are now inserted into Eq. (7) and (8). One has for this frequency range:

$$\bar{\eta} = \eta + \frac{\mu^2}{\omega^2 \eta} = \frac{\mu}{\omega}\left(\frac{\theta}{2\pi} + \frac{2\pi}{\theta}\right) \approx \frac{2\pi\mu}{\omega\theta}, \qquad (11)$$

and

$$\bar{\epsilon} = \epsilon_a + \frac{4\pi k \mu}{\mu^2 + \omega^2 \eta^2} \approx \epsilon_a + \frac{4\pi k}{\mu}. \qquad (12)$$

The second term in $\bar{\epsilon}$ results from an elastic shift of the ions. With $n = 10^{21}$ (see Table I) and $\lambda = 10^{-7}$ this term becomes about 3, with $n = 10^{20}$: 0·3, thus of the same order as ϵ_a itself. The theory indicates a finite contribution to the total dielectric constant, due to the elastic displacement of ions. Further, from (10) and (11):

$$\tan \delta = 2k\theta/\bar{\epsilon}\mu. \qquad (13)$$

With the numerical values as used above, it becomes about 10^{-3}, thus of the same order as dielectric losses of dipolar or other origin. It is—as long as Eq. (5) holds—independent of frequency, as generally encountered with technical dielectrics in this frequency range. Thus the theory shows a finite contribution towards dielectric losses due to pure ionic mechanism.

This seems to be a noteworthy result. Up to now it always has been maintained that the d.c. conductivity of solids is not sufficiently high to explain the a.c. losses. This is certainly true. Other mechanisms have been found and verified experimentally to account for those losses. The present analysis, however, shows that, even if those other mechanisms were not operative, the higher a.c. loss can be explained purely by the presence of the same ions, which lead to the d.c. conductivity. The reason is that the ionic mobility at alternating voltage is not any more controlled by the fairly high viscosity of the medium, but by its solid friction, which is several orders smaller.

V

Applying the model pictured in Section II to ions acted upon by a constant but high electric field, only a semi-quantitative deduction can be given, since a rigorous theory is probably even more difficult than that for a.c.

First it has to be noted that the model Fig. 1 evidently refers to the motion of the ion from one equilibrium position to another. The elastic displacement, as represented by the elongation of the spring 2, has only a meaning, if reckoned from an equilibrium position. It seems plausible to assume that the ion reaches always a new equilibrium, after having slipped past another molecule of the solid. The model therefore, refers to a total displacement of one molecular distance, λ.

The following consideration is concerned with the description of an ionic travel along this distance λ. This elementary process will repeat itself each time the ion has slipped into a new equilibrium position.

TABLE I. *Estimation of* η_0.

η_0	n	n/n_m
10^{15}	10^{24}	10^2
10^{14}	10^{23}	10
10^{13}	10^{22}	1
10^{12}	10^{21}	10^{-1}
10^{11}	10^{20}	10^{-2}

[8] A. Gemant, *Liquid Dielectrics* (Wiley, New York, 1933), p. 61.
[9] J. B. Whitehead and F. E. Mauritz, Electrical Engineering 56, 465 (1937).

The elementary process itself consists of an elastic and of a viscous displacement, λ_1, and λ_2. The first one occurs ever so much quicker than the second. If the effective, observable velocity of the ion is u, then the time λ/u is *practically* equal to that required to cover the viscous displacement λ_2. Since the (viscous) mobility is $e/\lambda\eta_0$ (the numerical factor of λ always left open), the corresponding velocity in a field E is $eE/\lambda\eta_0$, and we have the relation:

$$\lambda_2=\frac{eE}{\lambda\eta_0}\cdot\frac{\lambda}{u}. \tag{14}$$

For λ_1 we have Hooke's law, that is, due to the formal analogy of viscous flow and elastic displacement:

$$\lambda_1=eE/\lambda\mu. \tag{15}$$

Now in (15) the solid friction has been neglected. In reality a small fraction of E is used to overcome the friction in the element 3, and the corresponding part had to be deduced from the value as occurring in (15). However, this type of friction has here little importance, the element θ playing only the role of a correction term in this kind of motion. Later below, when numerical values will be inserted, we shall come back to this point.

From (14) and (15):

$$\lambda=eE/\lambda\mu+eE/u\eta_0, \tag{16}$$

or, solving for u:

$$u=\frac{eE/\eta_0}{\lambda-eE/\lambda\mu}. \tag{17}$$

Eq. (17) can be brought into a dimensionless form in the following way. Let us define a critical field strength E_c such that $\lambda_1=\lambda$, that is the whole displacement is covered elastically. Then from (15)

$$E_c=\lambda^2\mu/e \tag{18}$$

and in measuring the field strength in fractions of this critical value, we obtain the ratio $E^*=E/E_c$. Similarly we define a critical velocity u_c such that the whole molecular distance λ should be covered during a time equal to the time constant τ_0 of the system. Hence:

$$u_c=\lambda/\tau_0. \tag{19}$$

Again u^* should denote the ratio of the velocity u to the critical value u_c; $u^*=u/u_c$. Here we note the intimate connection of this consideration with that of the previous sections. In both the time constant τ_0 determines the range in which the viscous process gives way to the elastic one; but while in the a.c. theory τ_0 determines a certain frequency range, in the high field theory it determines a critical velocity. Putting all these values into (17), we obtain:

$$u^*=E^*/(1-E^*). \tag{20}$$

For small values of the field, we have $u^*=E^*$ which is equivalent to Ohm's law, since the whole motion is due to viscous flow. The more E^* becomes comparable with unity, the larger fraction of the total path is covered by means of elastic "jumps" of the ion, the larger the deviation from Ohm's law: the velocity will increase with the field stronger than linearly.

In considering this result it seems possible by its means to interpret the fact generally observed with solid dielectrics; namely, that the electric conductivity increases if the field strength is raised sufficiently high. Although the behavior of ions as shown above appears to be the *primary* cause of the observed effect, it must be emphasized that Eq. (20) does not by any means represent the conductivity as a function of field strength.

This can be seen directly by calculating the order of E_c from (18). With the values of the last section we have:

$$E_c\sim 10^5 \text{ abs.}=3\cdot 10^7 \text{ volts/cm}, \tag{21}$$

and from (20) it follows that for a field strength $3\cdot 10^5$ v/cm, 1 percent deviation from Ohm's law should be expected ($E^*=0.01$). From experimental work,[10] on the other hand, it is known that at 10^5 v/cm, and frequently much lower, the effect is sometimes quite considerable. This apparent discrepancy, however, can be clarified by turning our attention to the energy balance of the assumed type of motion.

VI

The above mechanism—elastic shifts interchanging with sections of viscous flow—requires

[10] S. Whitehead and W. Nethercot, Proc. Phys. Soc. 47, 974 (1935).

TABLE II. *Estimation of ionizing field strength.*

VOLTS/CM	x_i (CM)
10^3	200
10^4	2
10^5	$2\cdot10^{-2}$
10^6	$2\cdot10^{-4}$

that only a certain fraction of the work done by the electric field is converted into heat; namely, the fraction corresponding to viscous flow. The other part is turned into elastic energy. However, as the ion leaves each volume element, the strain of this latter is released and the question arises what will happen with the stored elastic energy.

While an exact answer to this question is not possible without knowing more about the actual molecular processes, it seems quite plausible to assume that each time the ion slips past a molecular barrier, the released energy is imparted to the ion in form of vibratory kinetic energy. Since possibly not the whole elastic energy undergoes this transformation (part of it being eventually dissipated) the following figures, based on the above assumption, will have the character of maximum figures.

Along a path x the total work done by the field is eEx, and that part which is stored as elastic energy, and is finally transformed into vibratory kinetic energy, L, of the ion is $eEx\lambda_1/\lambda$, or (see Eq. (15)):

$$L=e^2E^2x/\lambda^2\mu=eE^2x/E_c. \tag{22}$$

Thus we see that the ion continually gains kinetic energy. Although it will probably lose part of it during its phases of viscous flow, it will retain another part, until L reaches the ionization energy. Then it will lose the whole during an impact, giving rise to two new ions.

Assuming again optimal values to hold, the ionization energy, L_i will be collected during a length x_i, the latter being given by (22):

$$x_i=E_cL_i/eE^2. \tag{23}$$

Taking $E_c\sim10^5$ (Eq. (21)) and $L_i\sim10^{-11}$ (corresponding to an ionization voltage of ~5 volts), compared to which one degree of freedom of the average thermal energy ($\sim10^{-14}$) can be neglected, x_i becomes

$$x_i=2\cdot10^3/E^2.$$

The following Table II gives corresponding values of the field strength in v/cm (E is measured in absolute units) and x_i, the values of x_i being minimum values.

The thickness of dielectrics generally being of the order of 1−0.1 cm, it can be seen that ionization will not be noticeable below 10^4-10^5 v/cm, but will start and increase rapidly as this range is reached. As soon as ions are being produced by ionization, they will multiply exponentially, as known from the ionization theory of gases. This is the mechanism by which the increase with field strength of the conductivity will be controlled. If the field strength increases still further, other complicating processes will set in, such as ionization by electronic impact,[11] or an instability of thermal equilibrium,[12] both ultimately leading to breakdown of the dielectric.

Summarizing the results of the last two sections we see that the model assumed in Section II causes the ions to cover a little fraction of their total path by elastic displacement, instead of a viscous flow. This fraction being small, a direct increase of ionic mobility (Eq. (20)) will not generally be observable. Solid friction, correlated to the elastic shifts, has, therefore, no significance in this connection.

In making the plausible assumption that a large part of the elastic energy stored during the elastic displacement is converted into vibratory kinetic energy of the ion, the path can be computed, along which the ionization energy is being collected. This path is inversely proportional to the square of the field strength. Whereas up to 10^4 v/cm the number of ionizations will be vanishingly small, it becomes considerable in the range of 10^5 v/cm, as known from experiments on conductivity. Ionization will set in, ultimately leading to breakdown. Thus the field effect upon ions of our theory accounts for the way in which energies large enough to ionize can be accumulated by ions, in spite of the fact that the majority of their path is covered by a viscous flow.

[11] A. v. Hippel, J. App. Phys. **8**, 815 (1937).
[12] A. Gemant, "Thermal Instability of Dielectrics," J. Frank. Inst. in print.

The Dielectric Strength of Benzene and Heptane

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(Received October 13, 1938)

The dielectric strengths at 25°C of benzene and of heptane in a uniform electric field produced with a sphere gap and of heptane in a non-uniform field between concentric cylinders, were measured on the pure filtered liquids and with rigorous control of the electrode surface. With any one experimental procedure, the breakdown gradients were reproducible to within 5 percent provided all variables were carefully controlled. The most important of these variables, the character of the electrode surface, is influenced by such factors as the degree of polish or etching, adsorbed gas or ions, and the gases dissolved in the electrodes. Adsorbed oxygen or hydrogen, for example, induces incipient discharges in either liquid with molybdenum electrodes, but not in heptane with nickel electrodes; in the latter case, the gas adsorbed on the electrodes slightly increases the breakdown gradient. Below one atmosphere, the dielectric strengths of benzene and heptane are independent of the pressure. In a non-uniform field, the dielectric strength of heptane is the same for a.c. and d.c. of either polarity. Although reproducible dielectric strengths were obtained by any one experimental procedure, the results from different procedures varied from 100 to 1700 kv (Peak)/cm. It appears, therefore, that the dielectric strengths of pure liquids depend primarily on the nature of the electrode surface which varies with the experimental procedure.

INTRODUCTION

AS several reviews[1-4] show, the numerous investigations of the dielectric strengths of liquids have yielded exceedingly discordant results, probably for a number of reasons. When insulating oils are studied, for example, the samples are difficult to purify or reproduce. A pure compound, like benzene or heptane, is always reproducible, but its purification (especially the removal of foreign phases like colloidal dispersions or other suspended materials, all of which lead to discordant breakdown gradients) is of paramount importance. Even with carefully purified liquids and clean, highly polished electrodes, different dielectric strength values have been obtained by different experimental methods,[5, 6] suggesting that one or more of the variables involved had not been consciously controlled.

The present investigation was undertaken partly to discover whether thorough drying and degassing of the liquids and the complete removal of gas absorbed on or dissolved in the electrodes would yield experimental results that were independent of the particular procedure employed. The effect of hydrogen or oxygen adsorbed on the electrodes was also studied.

APPARATUS

In the present work a 60-cycle sinusoidal a.c. voltage was obtained from a 200-kv (peak) x-ray transformer grounded at one end. A motor-driven voltage regulator controlled the input voltage of this transformer and provided a continuously variable rate of voltage rise in the range 0.5 to 10 kv per second. Slower rates of voltage rise were obtained by intermittent operation of the driving motor.

Constant potential d.c. (± 1 percent) of either polarity was obtained by connecting a Kenotron and sufficient capacity to the transformer. Five capacitors (0.25 μf, 20,000 v) were connected in series and grounded at one end. The voltage was distributed uniformly on the condensers by means of a 260-megohm resistance which was provided with equally spaced taps connecting to each condenser.

A reliable voltage measuring system was obtained through the use of a capacity divider and a vacuum tube voltmeter (General Radio Co. No. 776A) which measures peak values of any wave shape. The construction of this voltage measuring system is shown in Fig. 1. A capacity

[1] S. Whitehead, *Dielectric Phenomena. II. Electrical Discharges in Liquids* (Ernest Benn Limited, London, 1928).
[2] A. Gemant, *Elektrophysik der Isolierstoffe* (J. Springer, Berlin, 1930).
[3] A. Nikuradse, *Das flussige Dielektrum* (J. Springer, Berlin, 1934).
[4] F. Koppelmann, Zeits. f. tech. Physik **16**, 125 (1935).
[5] W. Bahre, Archiv. f. Elektrotechnik **31**, 141 (1937).
[6] R. Bredner, Archiv. f. Elektrotechnik **31**, 351 (1937).

of about 10 $\mu\mu$f was obtained for the high voltage condenser by the use of two brass spheres (25 cm diameter) mounted with a separation of 50 cm from center to center. The one sphere was insulated by mounting on a herkolite cylinder and was permanently connected to the high voltage source. On the other sphere a segment (20.4 cm diameter) was insulated by mycalex supports and was connected to ground through a 0.012 μf mica condenser. The voltage drop on the mica condenser was measured with the vacuum tube voltmeter. The capacity divider and voltmeter were calibrated with 12.5-cm spheres using recent standardizing data.[7]

A Thyratron control circuit shown in Fig. 2 was always connected to the ground lead of the breakdown cell to minimize the destructive effects of the arc both on the liquid under investigation and the electrodes of the cell. This device served as an automatic switch which opened the primary circuit of the high voltage transformer within a few cycles after the breakdown arc forms. The protective gap of this circuit breaks down at 40 volts so that the transient high voltage resulting from the breakdown arc is not applied to the grid of the Thyratron.

Materials

Normal heptane (California Chemical Company, New York, New York) had the following properties based upon samples submitted to the National Bureau of Standards: b.p. 98.58°C; f.p. −90.88°C; n_D^{20} 1.3879; d^{20} 0.6842. This material was used without further purification.

Benzene (Merck reagent grade) was purified by three successive treatments with each of the following reagents: concentrated sulfuric acid, concentrated sodium hydroxide solution and mercury. The benzene was thoroughly washed with water after each treatment. The product was dried, recrystallized and fractionated after refluxing over sodium. b.p. 79.5–79.7°C; n_D^{20} 1.5014.

In certain experiments these liquids were filtered three times immediately before filling the breakdown cells. The repeated filtration served to remove any particles which were initially on the walls of the filtering flask. For this purpose only fritted glass filters (Jena, Fish-Schurman Corporation, New York, New York) were employed since paper filters introduced fibers. Filters with average pore size of 5–10 microns (porosity No. 4) had practically no effect as judged by ultramicroscopic examination of the liquid and breakdown gradients; whereas filters with average pore size of 1.5 microns (porosity No. 5) showed marked improvement by both criteria. The liquids were stored in glass-stoppered bottles so that they were saturated with air and contained traces of water.

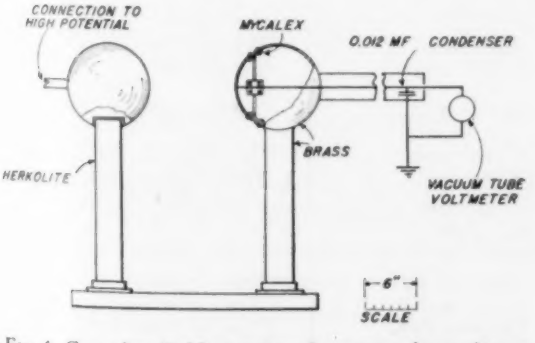

Fig. 1. Capacity divider system for measuring voltage.

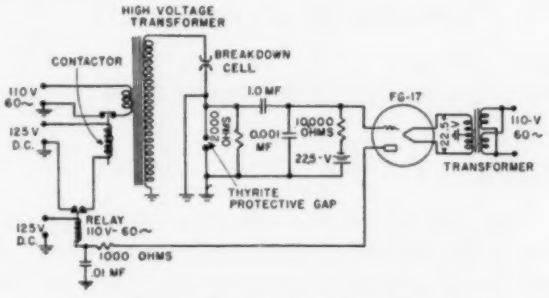

Fig. 2. Thyratron control circuit.

Procedures and Results

In the present investigation no correction has been made for non-uniformity of the field intensity between equal spheres, one grounded. The ratio of the electrode gap to the radius of the electrodes was chosen so that this correction was always less than 5.0 percent as given by the calculation of Russell.[8] All dielectric strength

[7] Elec. Eng. 55, 783 (1936).

[8] A. Russel, Phil. Mag. 11, 257 (1906).

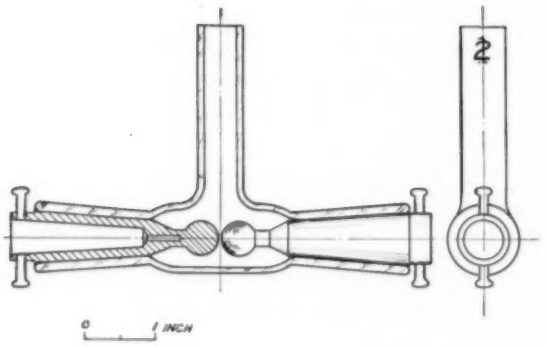

FIG. 3. Quartz cell for procedure 1.

experiments were carried out at room temperature (25°C).

Procedure 1

The cell design and cleaning procedure employed by Bahre[5] and Bredner[6] were found to give reproducible results. Several cells of the type shown in Fig. 3 were constructed of quartz. Identical results were obtained with electrodes of stainless steel (18–8) and of chromium-plated steel. When the plating was worn thin by buffing, the electrodes were slightly etched by the cleaning acids and low breakdown values were obtained. In Procedure 1 only the first breakdown for a given cleaning and filling of the cell was recorded. The essential details of this procedure, such as buffing, electrolytic cleaning, acid treating, and steaming of the electrodes and cell, were the same as given by Bahre.[5] Several variations in the acid treatment for the electrodes were employed before the electrolytic cleaning as indicated along with the results in Table I. In certain cases (as indicated in Table I) the quartz cells were heated to a dull red in a Bunsen flame after the steaming operation. The voltage was raised at about 1 kv/sec. and no resistance was used in series with the cell for the breakdown measurements.

Procedure 2

This procedure was designed to permit the determination of breakdown gradients of completely degassed and dehydrated liquids under conditions that controlled the electrodes in regard to adsorbed or dissolved gases. The cell used in this procedure is shown in Fig. 4. The hemispherical electrodes were made by welding molybdenum or nickel punchings to a flexible web which permitted high frequency firing without distortion or mechanical failure. The molybdenum cells were electrolytically cleaned in concentrated sulfuric acid; the nickel cells were similarly cleaned in a nickel-plating solution. These electrodes were initially buffed to a mirror-like finish; but this finish could not be maintained during the cleaning and degassing treatments.

TABLE I. *Procedure 1. a.c. 60 cycle—no series resistance. Pressure: 1 atmos., liquid: air saturated.*

Exp. No.	No. of Breakdowns	Gap cm	Breakdown Gradient kv (Peak)/cm	Mean Deviation percent	Liquid	Electrode Treatment	Quartz Treatment
			Benzene				
16	7	0.0635	560	2.4	Unfiltered	Acetic acid	Cleaning soln.
22	2	0.1220	580	1.0	Unfiltered	Acetic acid	Cleaning soln.
26	1	0.1220	665				
29	1	0.0635	650	0.9	Filtered	Acetic Acid	Cleaning soln.
30	1	0.0305	655				
31	5	.0460–.1220	820	4.0	Filtered	Cleaning soln.	Cleaning soln., ignited
32	3	0.0305	1115	5.0	Filtered	Nitric acid	Nitric acid, ignited
			Heptane				
8	Not reproducible		480–620		Unfiltered	Acetic acid	Cleaning soln.
9	3	.0460–.0970	730	3.0	Filtered	Acetic acid	Cleaning soln.
15	9	.0635–.1220	820	2.7	Filtered	Cleaning soln.	Cleaning soln., ignited
24	5	.0305–.1220	670	4.8	Filtered	Nitric-sulfuric acid	Nitric-sulfuric acid, ignited
31	5	.0330–.1220	1220	3.7	Filtered	Nitric acid	Nitric acid, ignited

These cells were degassed and sealed off under high vacuum until used.

The initial drying and degassing of the liquid was similar to the final operations which are described. In this preliminary drying the liquid was treated twice with clean sodium and vacuum-distilled twice after degassing. The cell-filling system, shown in Fig. 5, was designed to carry out the final drying and degassing operations, as well as the filling of the cell, under the high vacuum conditions obtained after heating and evacuating the glass system for one hour at 450°C. After a bake-out the electrodes were again degassed by high frequency heating and the cell isolated from the pumps by closing constriction 1. The liquid in the lower bulb was cooled with liquid nitrogen and transfer seal 2 was broken by moving the steel ball with a magnet. The sodium capsule in the upper bulb was broken by high frequency heating and constriction 3 sealed. The liquid was slowly distilled into the upper bulb where it was refluxed over the sodium after constriction 4 was sealed. After the liquid had refluxed for 30 minutes, it was cooled with liquid nitrogen and the evolved hydrogen was evacuated by breaking transfer seal 5. The refluxing was repeated after closing constriction 5 while the final evacuation was obtained by breaking seal 6. After closing constriction 6, the liquid was slowly distilled into the cell which was then cooled by solid carbon

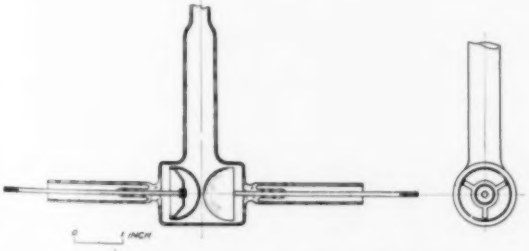

FIG. 4. Molybdenum or nickel cell design.

dioxide to avoid decomposition during the final seal-off at constriction 8. In certain experiments oxygen was admitted through a silver tube attached to the cell; hydrogen, by means of a palladium tube. The electrodes were heated to about 600°C and cooled in the presence of the gas, 5 mm pressure in the case of hydrogen or 0.1

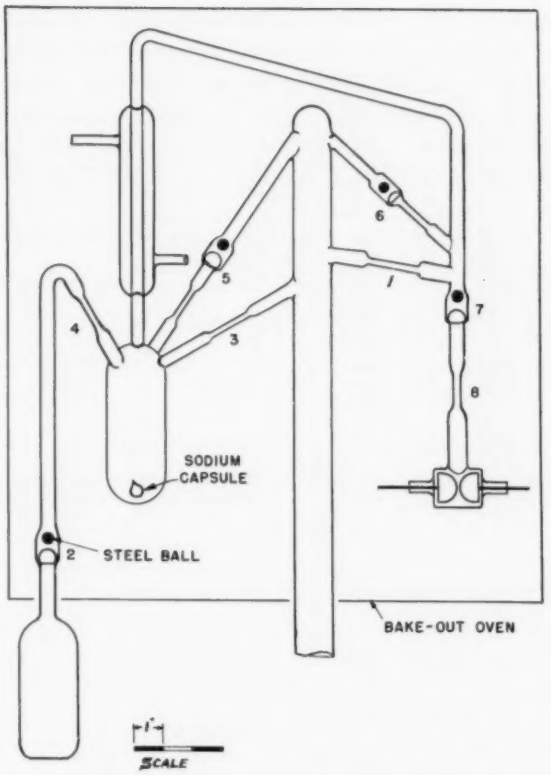

FIG. 5. Vacuum system for filling cells.

mm of oxygen. The excess gas was pumped off before filling the cell. In the experiments with oxygen no visible films (interference colors) were formed on the electrodes.

In this procedure, also, only the first breakdown gradient was regarded as significant. The breakdown was usually taken on the gas-free liquid, although some cells were open to the atmosphere to obtain the effect of pressure on the breakdown gradient. Reproducibility of the breakdown gradients with this procedure was more difficult to achieve and high values were never attained. The results obtained with this procedure are summarized in Table II. The electrodes were cleaned and degassed before each experiment. Unless otherwise noted the pressure on the liquid at the center of the electrodes was the vapor pressure plus 6–8 cm of the liquid. The rate of voltage rise was the same as in the previous procedure.

The liquid for Experiments 32 and 34 was prepared by the process described by Martin[9] for

[9] W. H. Martin, J. Phys. Chem. **24**, 478 (1920).

TABLE II. *Procedure 2.*

Exp. No.	Cell	Gap cm	Breakdown Gradient kv (Peak) / cm	Mean Deviation per cent	
			Benzene		
1	Mo-2	0.122	209	6.8	
5	Mo-1	.133	192		
20	Mo-6	.117	170		
9	Mo-2	.122	112*	7.8	Adsorbed O_2
10	Mo-4	.105	135*		
11	Mo-5	.177	137*		
13	Mo-1	.139	174*	27.0	Adsorbed H_2
14	Mo-5	.173	83*		
18	Mo-7	.131	108*		
32	Mo-6	.117	304	5.5	Optically clear
34	Mo-5	.198	272		
23	Mo-5	.202	98	7.1	Electrodes exposed to air, filtered, air saturated benzene. Pressure 1 atmos.
24	Mo-9	.126	113		
			Heptane		
6	Mo-1	0.133	192	4.9	
16	Mo-8	.117	183		
18	Ni-18	.131	226		
20	Mo-8	.114	112*		Adsorbed O_2
27	Ni-17	.117	305		
22	Mo-16	.097	132*		
23	Ni-18	.132	334	5.0	Adsorbed H_2
25	Ni-18	.132	302		
28	Mo-6	.114	360		Air admitted after filling cell, 1 atmos.
29	Mo-8	.117	280		
21	Ni-17	.109	600	5.3	Electrodes exposed to air, filtered, air saturated heptane. Pressure 1 atmos.
21	Ni-18	.132	541		

* Incipient discharges.

obtaining optically clear liquids. The essential feature of the process is distillation without ebullition and repeated washing back of the distillate. This process was carried out as the final step in filling the cell and involved the use of a small bulb attached directly to the cell.

Procedure 3

In this procedure a dumbbell cell (Fig. 6), consisting of a tungsten filament mounted under spring tension in the axis of a glass tube, was used. The inner surface of the glass was either gold-coated by burning on a gold paint or nickel-coated by evaporation from a filament. These cells were thoroughly evacuated by baking at 450°C and then the filament was degassed by heating at 2300°C for ten minutes. In this cell (two concentric cylinders) a non-uniform voltage gradient is obtained since the maximum gradient occurs at the surface of the filament. The voltage gradient (F) at the surface of the filament was calculated from the observed breakdown voltage (V) by the equation:

$$F=\frac{V}{r_1 \ln (r_2/r_1)},$$

where r_1 and r_2 are the radii of the filament and the cylinder, respectively. The filament was always connected to the high voltage source. Preliminary experiments showed that the breakdown voltage of heptane with this cell was satisfactorily reproducible for twenty successive breakdowns in the same liquid sample. No systematic trend occurred in the values for the successive breakdowns. It was necessary, however, to show that the breakdown gradient was independent of the size of filament used. For this purpose a number of cells were made from five-eighth and one-inch glass with various size filaments. The results of this study are summarized in Table III. The mean deviation is based on ten successive breakdowns in the same liquid. The cells for these experiments were maintained under vacuum until immediately before use, when they were opened to the atmosphere, rinsed only once with filtered heptane and filled. The rate of voltage rise was 0.1 kv/sec. and no protective resistance was used in series with the cell. In the procedures involving sphere gaps, the breakdown arc was stable; whereas the breakdown arc occurring in the dumbbell cells

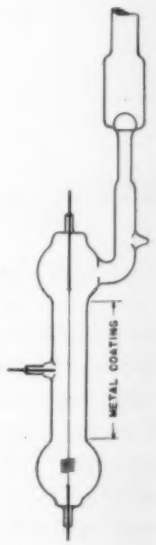

FIG. 6. Dumbbell cell.

most frequently quenched itself, giving rise to a sharp clicking noise. The craters sometimes formed on the filament as a result of the arc were easily seen with a low power microscope.

Since reproducible results were obtained with the dumbbell cell, experiments were undertaken to discover the effect of d.c. potentials on the breakdown gradients. The effect of maintaining the voltage at 0.8 of the breakdown value was also investigated, since the application of an electric field is a well-known means of removing colloidal or ionic impurities. The first four experiments listed in Table IV were made with air-saturated heptane which had been filtered three times. The cells for these experiments were rinsed three times with filtered heptane. The underscored values of Table IV represent values which were reproduced by rinsing the cell and filling with a fresh sample of filtered heptane. The superscripts in this table indicate the order in which the various breakdown gradients were determined. The second column of a.c. values given in this table were obtained by raising the voltage to 0.8 of the breakdown value where it was held constant for 1 minute before raising the voltage to breakdown. The preliminary experiments showed a definite increase in the average breakdown gradient as a result of this treatment; the increase was most pronounced on a.c. potentials and rather less significant on d.c. potentials. Thorough rinsing of the cell with filtered heptane eliminated the effect, while dried, degassed heptane never exhibited this effect.

TABLE III. *Filtered heptane 1 atmos. Cell exposed to air. a.c. No series resistance. W filament—nickel-coated cylinder.*

Filament Diameter cm	Cylinder Diameter cm	Average Breakdown Gradient kv(peak)/cm	Mean Deviation† percent
0.0381	1.59	600	1.9
.0254	1.59	610	4.5
.0127	1.59	630	2.3
.0076	1.59	640	2.0
.0025	1.59	830*	5.3
.0254	2.54	625	2.0
.0127	2.54	635	6.0
	Average	625	3.2

* Omitted in average.
† Based on ten successive breakdowns in the same liquid.

The last five experiments listed in Table IV were obtained with dried and degassed heptane using the vacuum technique described in Procedure 2. The filaments were flashed for one minute at 2300°C immediately before distilling in the heptane. The polished filaments were obtained by the procedure described by Johnson[10]

TABLE IV. *Heptane. Average breakdown gradients kv (peak)/cm. Tungsten filament.*

	Exp. No.	Filament Diameter cm	a.c.	(I)	d.c. Filament (−)	d.c. Filament (+)
Filtered 1 atmos.	59	0.0025			(1) 1520±1.5%	(2) 2080
	54	.0038*	(3) *1700±4.0%*	(4) 1790±1.7%	(1) 1150+2.0	(2) 1300±4.0%
	55	.0051			(1) 975±1.0	(2) 1080
	60	.0076	(1) 945±3.7	(2) 1030±2.5		
Dried degassed vacuum	63	0.0025	(3) *1040±5.0*	(4) 1030±5.1	(1) *1005±2.5*	(2) 1080±1.0
	66	.0025	985±5.0			
	58	.0038*	(3) 1000±4.5	(4) 1000±3.0	(1) *1280±5.3*	(2) 1000±4.0
	57	.0051	(3) 1115±1.5		(1) 1030±1.5	(2) 955±4.0
	67	.0076	(2) 1000±3.0		(1) 1000±3.0	
Average			1028	1015	1079	1012

* Polished filament.
(*I*) Voltage held at 0.8 of breakdown value for 1 minute before taking breakdown.

which removed the die marks normally present on tungsten wire. All d.c. values were obtained with a protective resistance of one megohm in series with the cell. The average values were obtained from five successive breakdowns; in cases where the mean deviation is not given, only one value was obtained because the filament was burned off.

Discussion

The fundamental purpose of the elaborate cleaning operations employed in Procedure 1 was to obtain a reproducible electrode surface with respect to polish and adsorption. The electrolytic cleaning and acid treatment effectively remove the residual monofilm which withstands scrubbing and solvent action. Merely touching the electrode surface with the fingers after this operation caused low erratic results. The same effect was obtained by applying a monofilm of barium

[10] R. P. Johnson, Rev. Sci. Inst. 9, 253 (1938).

stearate. The steaming operation is probably the most effective means of eliminating dust particles from the surfaces of the cell, as pointed out by Garrard[11] in the preparation of dust-free liquids. The importance of adsorption on the electrode surface is emphasized by the results obtained by varying the acid treatment of the electrodes. It is believed that these differences are to be attributed to the electrode surface rather than the quartz since the latter was heated to 600–700°C after the acid treatment and steaming. The identical behavior of stainless steel and chromium surfaces is not surprising since the protective film is probably the same in both cases.

Procedure 1 gave satisfactorily reproducible values for the breakdown gradient of unfiltered benzene; the average of the nine breakdowns (Experiments 16 and 22) with this procedure is 570±2.1 percent kv (Peak)/cm. This procedure, however, was not satisfactory for heptane; this difference probably arises from the greater amount of suspended matter in the heptane which was used without further purification. The importance of removing suspended matter from liquids under dielectric strength tests has been demonstrated previously.[12] This difficulty with heptane vanished completely when the liquid was filtered as in Experiment 9 for which the average breakdown gradient was 730 kv (Peak)/cm±3.0 percent. A smaller percentage increase in the breakdown gradient was obtained with benzene as a result of filtration where the average value became 655 kv (Peak)/cm±0.9 percent.

The cleaning solution treatment of the electrodes and firing of the quartz cell in Experiments 15 and 31 gave agreement in average breakdown gradients for benzene and heptane at 820 kv/cm. The use of a nitric-sulfuric acid solution (Experiment 24) in place of cleaning solution decreased the average breakdown gradient probably because of the slight etching attack of this reagent on the electrode surface. The highest values of average breakdown gradient were obtained with hot concentrated nitric acid as used in Experiments 31 and 32 where the values for benzene and heptane were 1115 and 1220 kv (Peak)/cm, respectively. Bahre[5] and Bredner,[6] using this procedure and a protective resistance (1 megohm) in series obtained somewhat higher values for benzene, 1280 and 1450 kv (Peak)/cm, respectively. The agreement of the present values with these is satisfactory in view of the specific effects which have been found in the present work.

The breakdown gradients and the reproducibility which were obtained with Procedure 2 were much lower than anticipated; however, certain qualitative conclusions may be drawn from the results in Table II which emphasize the predominant role of the electrode surface with respect to adsorbed gas in dielectric strength experiments. The breakdown gradient for dry, gas-free benzene with gas-free molybdenum electrodes was 190 kv (Peak)/cm ±6.8 percent. A factor which may contribute to this low breakdown value is the slight etching of the electrode surface resulting from cleaning and degassing processes. Experiments with Procedure 1 have indicated this effect of etched electrode surfaces. The low total pressure on the liquid cannot contribute appreciably to this effect, since there is ample evidence to show that pressure has no effect on the dielectric strength of liquids in the absence of gas bubbles and suspended matter.[5, 12] The values (98 and 113 kv (Peak)/cm) for filtered benzene obtained at atmospheric pressure in Experiments 23 and 24 for the molybdenum electrodes exposed to air are also inconsistent with a pressure effect. It seems best to regard this low value (190 kv (Peak)/cm) as characteristic of dry, gas-free benzene with completely degassed molybdenum electrodes.

The experiments with adsorbed oxygen or hydrogen on molybdenum electrodes very conclusively demonstrate the primary importance of the electrode surface. Hydrogen is only slightly soluble in molybdenum while no solubility data are available for oxygen in molybdenum.[14] In every experiment with these gases adsorbed on the molybdenum, incipient discharges occurred in the dielectric strength determination. The

[11] J. D. Garrard, Trans. Roy. Soc. Canada (iii) **18**, III, 126 (1924).
[12] J. Sorge, Archiv. f. Elektrotechnik **13**, 189 (1924).
[12] A. Walter and O. Tscheljuskima, Tech. Physics, USSR **3**, 940 (1936).
[14] C. J. Smithells, *Gases and Metals* (Chapman & Hall, London, 1938).

incipient discharge is an unstable arc which usually quenches itself and is insufficient to trip the Thyratron protective device. Such incipient discharges, "*Vorentladungen*," have been observed frequently with liquids containing suspended matter.[12, 15] An accurate determination of the breakdown gradient was more difficult under these conditions. The adsorbed gas, however, definitely reduced the breakdown gradient of benzene about 50 percent. Gemant and Edler[16, 17] have proposed theories for the electrical breakdown in liquids based on the desorption of gas from the electrodes, which explains the formation of incipient discharges as a result of this process. It is perhaps significant that with molybdenum electrodes exposed to air the breakdown gradient of filtered benzene at atmospheric pressure (Experiments 23 and 24) is practically the same as for dried and degassed benzene at a few centimeters pressure with adsorbed oxygen on the electrodes. The only difference in the two cases was the occurrence of incipient discharge at the low pressures; these discharges may be favored by the low pressure. The highest average breakdown gradient (288 kv/cm ±5.5 percent) for dried and degassed benzene with the molybdenum cell was obtained in Experiments 32 and 34 where the cell was repeatedly washed with a distillate formed without ebullition to obtain an optically clear liquid. This experiment shows that suspended matter in the liquid phase is not responsible for the low breakdown gradients with this procedure as compared in Procedure 1.

The results for heptane with Procedure 2 are quite similar to those for benzene; in addition, experiments showing the effect of adsorbed hydrogen and oxygen on nickel electrodes are available. The average breakdown gradient (188 kv (Peak)/cm ±4.9 percent) of dry, gas-free heptane with gas-free molybdenum electrodes is practically identical with the value for benzene, while a slightly higher value (226 kv (Peak)/cm) is obtained under similar conditions with nickel electrodes. The effect of adsorbed hydrogen or oxygen on molybdenum electrodes is the same for heptane and benzene. It is thus probable that the incipient discharges and lowered breakdown gradients are exclusively electrode phenomena. Hydrogen or oxygen adsorbed on or dissolved in nickel electrodes caused a 30 percent increase in the breakdown gradient of heptane and induced no incipient discharges. The opposite effect of these gases with molybdenum and nickel must arise from different adsorption mechanisms in the two cases. It was noted previously that hydrogen and oxygen are only slightly soluble in molybdenum whereas in nickel hydrogen is quite soluble and oxygen is probably slightly soluble.[14]

The increase of 50–75 percent in the breakdown gradient of heptane obtained by admitting air to the molybdenum cells after filling is rather difficult to explain. A pressure effect does not seem very probable as in previous cases with benzene so that the effect probably arises from adsorption on the electrodes. A similar effect was obtained in Experiment 21 where a high breakdown gradient (570 kv (Peak)/cm ±5.3 percent) was observed with filtered heptane and degassed nickel electrodes which had been exposed to air. These conditions might result in a greater adsorption of oxygen than was obtained in Experiment 27 and hence a further increase in breakdown gradient. There is, however, no supporting evidence for this view.

The breakdown gradients determined by Procedure 3 were obtained only for heptane. The results in Table III justify the use of concentric cylinders for the determination of dielectric strength of liquids since the calculated breakdown gradients at the surface of the filament are constant and independent of the filament diameter with one exception which was obtained with the smallest filament. Microscopic examination of tungsten filaments reveal quite deep die marks and surface irregularities whose depth is roughly proportional to the wire diameter. The voltage gradient at such irregularities may exceed the gradient calculated for a true cylindrical surface by at least a factor of two. During the flashing of the filament (2300°C) the irregularities will smooth out more rapidly on the small filaments since there is less material involved. Successive breakdowns on a filament may cause increased breakdown gradients by burning off

[15] F. Schroter, Archiv. f. Elektrotechnik **12**, 67 (1923).
[16] A. Gemant, Zeits. f. Tech. Physik **9**, 398 (1928).
[17] H. Edler, Archiv. f. Elektrotechnik **24**, 37 (1930).

surface projections or decreased breakdown gradients by crater formation as a result of the arc. Examples of both trends have been observed.

The first four experiments in Table IV with the dumbbell cell containing air-saturated filtered heptane indicate that an essential variable is not controlled. There is a pronounced trend in the values with respect to filament diameter even when Experiment 54 is excluded since a polished filament was used in this case. This factor is probably the regularity or the polish of the surface of the filament. The degassing treatment (heating at 2300°C) undoubtedly removed more irregularities from the small filaments since the same time interval was used for all filaments. It should be noted that all die marks are removed from a filament by a.c. heating in vacuum for about 40 hours at 2300°C. The highest value found for the dielectric strength of heptane in the present work was the single value at 2080 kv (Peak)/cm in Experiment 59. The filament was burned off, however, as a result of this breakdown arc. The sequence of measurements in the case of Experiment 54 (polished filament) was as follows: 1150, 1300, 1700 and 1790 kv (Peak)/cm as indicated by the superscripts in Table IV. After these measurements the cell was rinsed and filled with a fresh sample of filtered heptane and the a.c. value obtained was 1700 kv (Peak)/cm ±4.0 percent indicating that the variation in values was due to changes on the filament surface. This trend may arise from the burning off of submicroscopic projections on the filament surface.

More satisfactory reproducibility of the breakdown gradient was obtained in the last five experiments given in Table IV where dried and degassed heptane was used. The average of all values (a.c. and d.c.) obtained with the vacuum technique is 1038 kv (Peak)/cm ±5.7 percent. The final line of Table IV indicates no significant difference in the breakdown gradients dependent upon the type of potential employed. In several experiments the cells were opened to the atmospheres and the same breakdown gradients were observed; thus demonstrating the absence of any pressure effect. It is further to be noted that the underscored values were reproduced within the given deviations after opening the cell, rinsing and refilling with filtered heptane. This behavior again indicates the predominant role of the electrode surface in dielectric strength experiments and the subordinate role of the liquid. In the vacuum procedure the filaments received an additional degassing treatment (flashing at 2300°C) before the cell was filled. This additional treatment should produce more uniform surfaces than were obtained in the experiments with air-saturated heptane. This fact may account for the smaller spread in the values obtained with the vacuum procedure.

The data of Table IV do not show any effect of maintaining a constant a.c. voltage gradient for one minute before determining breakdown. Similar experiments with d.c. potentials gave no change in breakdown gradient. Longer time intervals were also tried without any effect. Some preliminary results (not tabulated) indicated a difference in the d.c. breakdown potential gradient dependent upon the polarity of the filament. These effects, however, were not found in the experiments in which the cell was rinsed several times with filtered heptane. An increase in the breakdown gradient was found as a result of maintaining an electric field on unfiltered heptane. This effect has, therefore, been ascribed to suspended matter in the liquid.

The dielectric strength of benzene and heptane in a uniform field was found to be dependent upon the adsorbed gas or ions on the electrodes to a very marked degree, even when the liquids were carefully purified. In the case of heptane it was found that the dielectric strength was not the same with a uniform and non-uniform electric field even when the liquid is thoroughly dried and degassed and the electrodes are clean and completely degassed. In a non-uniform field (concentric cylinders) the dielectric strength of heptane does not seem to be affected by oxygen adsorped on the electrodes.

Electron Diffraction Study of Copper Oxides

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(Received January 28, 1939)

This paper describes an electron diffraction study of copper oxides formed from evaporated copper by exposing it in an oxygen atmosphere at various temperatures for various lengths of time. It also discusses several of the orientations which were observed in the evaporated copper.

THE films were prepared by vaporizing the copper and condensing the vapor in a vacuum of approximately one micron on microscope cover glasses. Only deposits thick enough to be opaque to light were used. The oxide was formed on the films by placing them in an adjustable-temperature oxygen-atmosphere electric furnace. The thin cover glasses used as a base for the films were a half-inch in diameter. These were supported in the furnace by three glass "fingers" directly over the bulb of the thermometer from which the temperature readings were taken. The temperature of the furnace was maintained constant to within plus or minus one degree centigrade. The electron diffraction camera used to obtain the crystal patterns was similar to many described in the literature.[1] All photographs were taken using electrons having a velocity corresponding to a wave-length of 0.063 angstrom and a camera length of 36.5 centimeters.

[1] G. I. Finch, Proc. Roy. Soc. Lond. **A141**, 399 (1933).

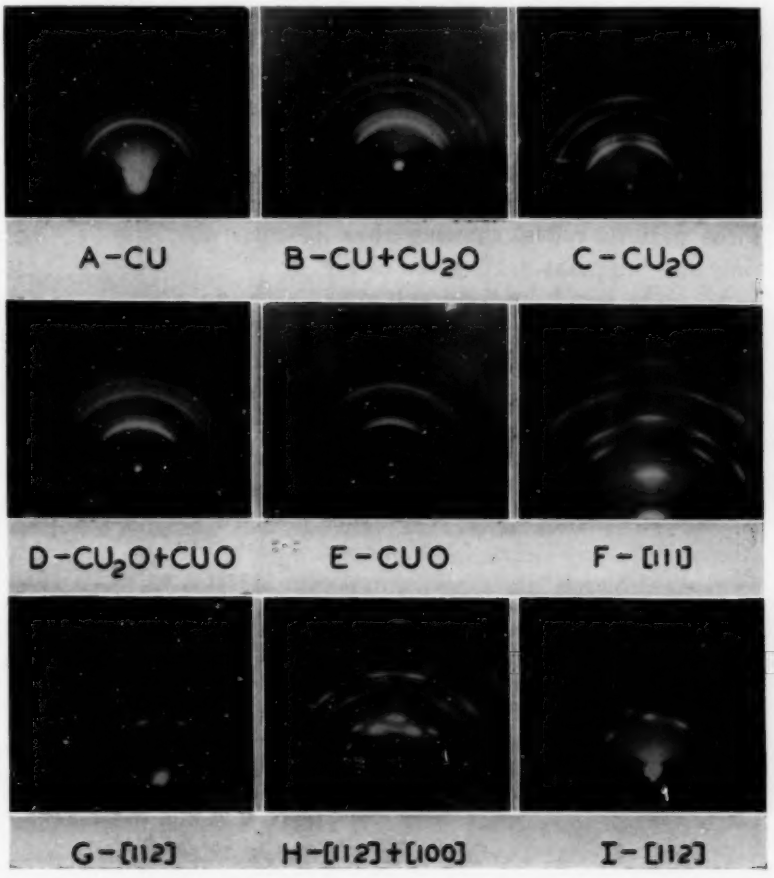

FIG. 1. Types of electron diffraction patterns obtained when evaporated copper films were oxidized at various times and temperatures in an oxygen atmosphere (*A*, *B*, *C*, *D*, *E*) and types of orientations observed (*F*, *G*, *H*, *I*).

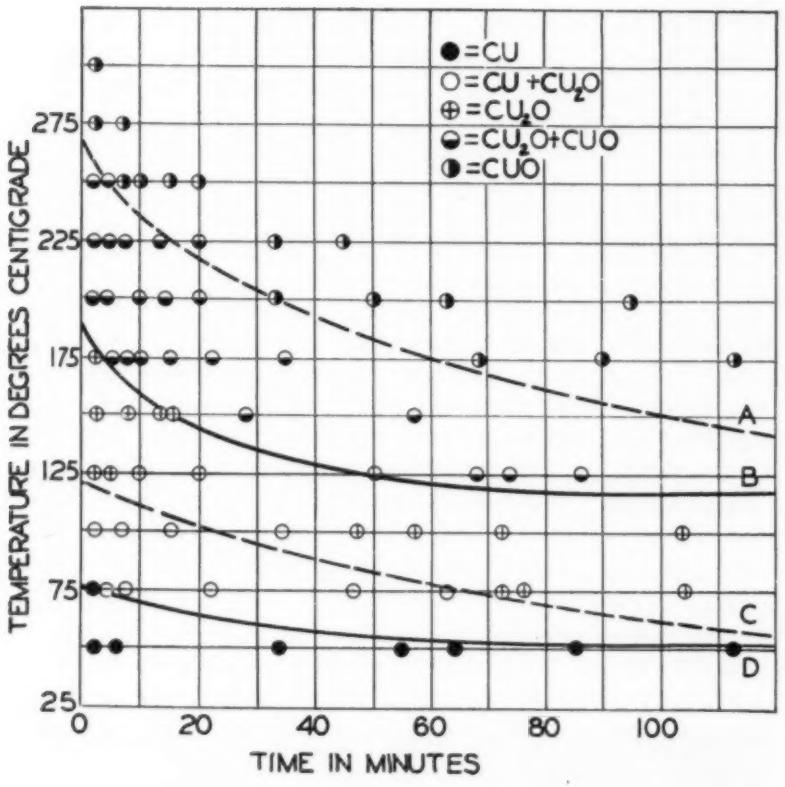

FIG. 2. Graph showing the kinds of copper oxide obtained when evaporated copper films were oxidized at various temperatures for various lengths of time. Curves *A*, *B*, *C*, *D* approximately separate the several oxides and combinations. These curves all tend to become horizontal, with curve *A* approaching *B* and curve *C* approaching *D*.

Five types of patterns dependent on the temperature of the furnace and the time of exposure of the films were observed. These are shown in Fig. 1 (*A*, *B*, *C*, *D*, *E*). A plot made of these pattern types, showing their relation to time and temperature, is given in Fig. 2.

As can be seen from the graph, rough zones are formed in which only one type of pattern occurs. At temperatures of 50°C or below, the copper films are very resistant to oxidation; exposures in an oxygen atmosphere at these temperatures yield no trace of oxide. (Longer exposures for films prepared by condensation are unsatisfactory since they give very faint patterns.) Above 50°C and below 275°C cuprous oxide is formed, although at temperatures over 125°C the Cu_2O oxide is unstable and soon changes in an oxygen atmosphere to cupric oxide. At temperatures above 275°C only the CuO form of copper oxide is obtained.

Many of the copper films prepared for this experiment were found to be composed of crystals oriented in such a way as to have one or two sets of planes parallel to the glass base of the films. These are shown in Fig. 1 (*F*, *G* and *H*). Deposits in which the (111) planes were all parallel to the glass base were observed more frequently than any other. The (100) orientation was never observed alone but occurred only with the (112) orientation. It would seem from the pattern obtained that the two orientations are equally distinct. If this is so, we have a contradiction to Dr. Dixit's[2] statement in his theory of orientations that ". . . two equally distinct orientations are never seen."

A few diffraction patterns were obtained which indicated a tilt of the oriented crystal planes. (See Fig. 1—I.) Burges'[3] explanation that this occurs when the vapor beam strikes the glass base at an angle less than 90° is correct as far as we have been able to observe.

[2] K. R. Dixit, Phil. Mag. **16**, 1049 (1933).
[3] W. G. Burges, Physica **1**, 549 (1934).

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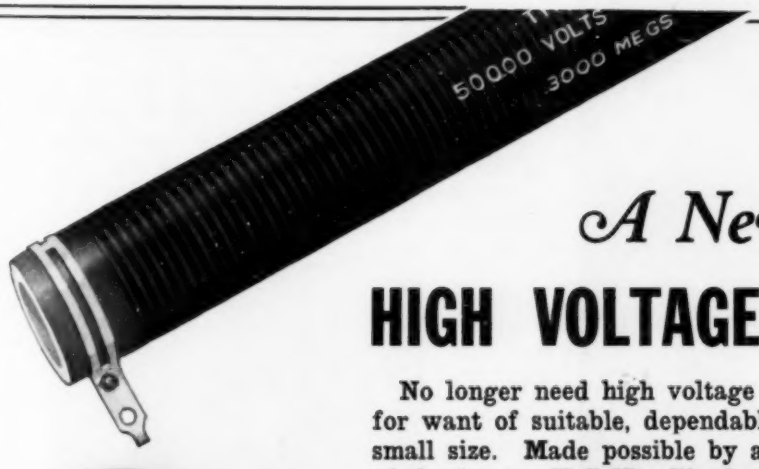

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Innovations in Instruments

Cathode-Ray Null Detector

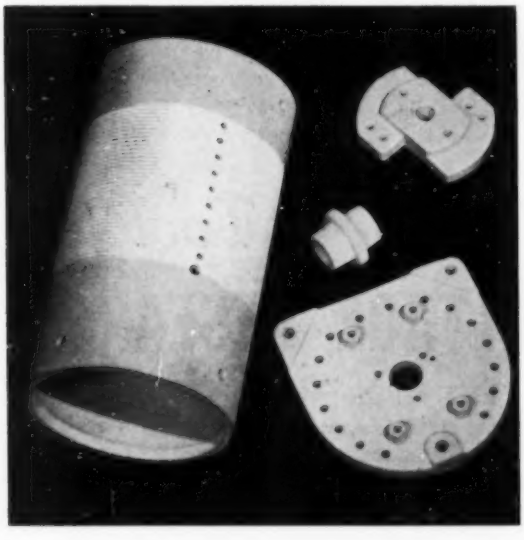
The cathode-ray null detector for a.c. impedance bridges, recently described by Lamson,[1] has been brought out in commercial form by the General Radio Company. Designed particularly to facilitate balancing bridges which show a "sliding balance," this null indicator separates the effects of adjustments of the resistive and the reactive balance controls, so that either component of the unknown impedance can be precisely balanced with only an approximate balance for the other component.

The indicating element is a one-inch cathode-ray oscillograph. A high gain amplifier provides the necessary sensitivity. Selectivity against harmonics is obtained by a selective degeneration circuit.[2]

[1] Horatio W. Lamson, "An Electronic Null Detector for Impedance Bridges," Rev. Sci. Inst. **9**, 272 (1938).
[2] H. H. Scott, "A New Type of Selective Circuit and Some Applications," Proc. I. R. E. **26**, 226 (1938).

Machinable Ceramic Material

The American Lava Corporation, Chattanooga, Tennessee, has recently put on the market a new ceramic material which carries the designation "Alsimag 222" and is a further addition to other Alsimag ceramics with defined dielectric and mechanical properties.



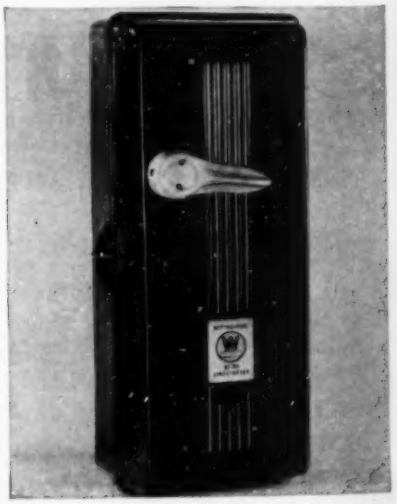
Alsimag 222 has the outstanding property that it can be machined after it has acquired strength by being fired. This makes it an ideal material for inventors, research men, and development engineers who frequently have to build working models and do not want to go into the initial expense of costly dies for sample work. They can do their experimental work on machined insulators made of Alsimag 222 and, after having established the shape and size required, the final product can be substituted by another Alsimag material most suitable for the specific purpose.

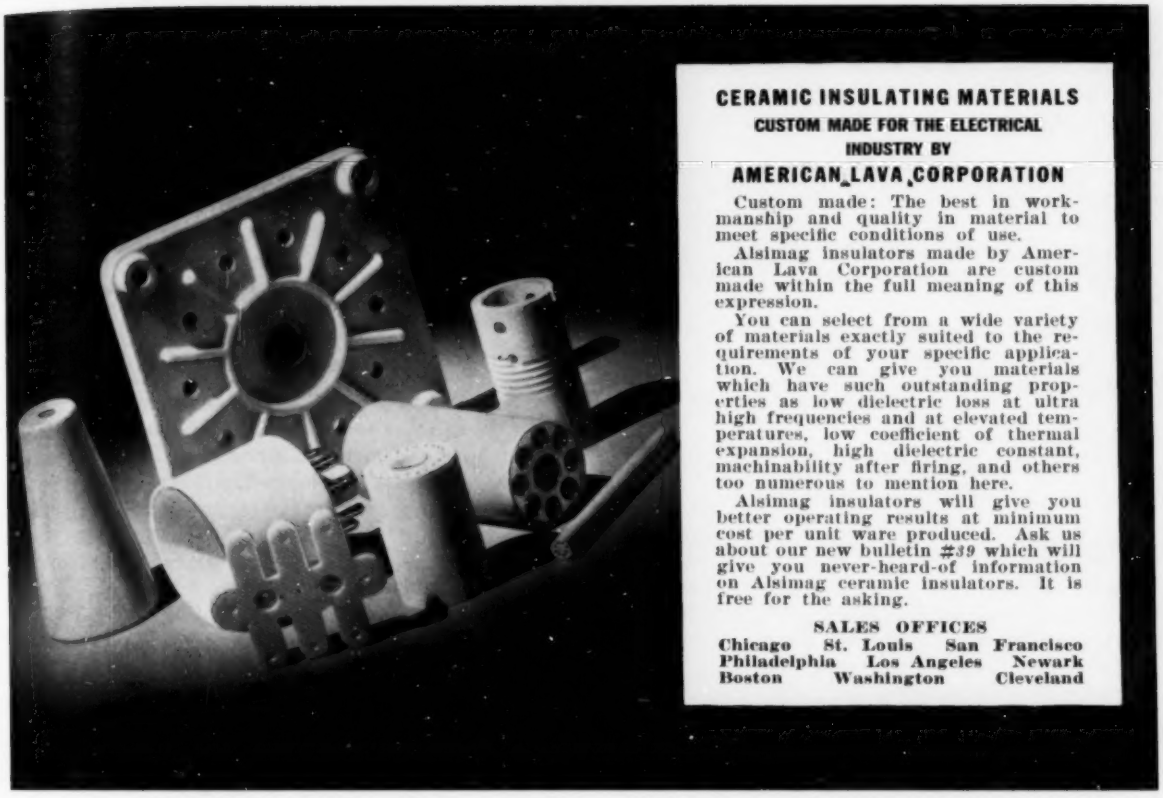
Alsimag 222 is a porous material of good mechanical strength. It can be turned on a lathe or milled like steel. Naturally, the material is quite abrasive and it is necessary to use tools with Carboloy (Tungsten Carbide) tips. Working instructions are given with the supply of the material. Alsimag 222 can be used up to 2500°F, suggesting its application for burners and heating supports. It has good dielectric properties and shows low dielectric loss at high frequencies, giving it useful applications in the electronic field.

Alsimag 222 is supplied in round stock or in tubular form in various sizes up to 3" diameter, also in disks and plates up to 10" diameter. Special shapes can be cut to specifications upon request. The American Lava Corporation undertakes to make customer's sample work in this material to exact or absolute dimensions of drawings. As there would be no delays through firing and few of the usual manufacturing losses such as occur through breakage, quick delivery of samples at fairly moderate cost can be made from Alsimag 222.

New De-Ion Combination Linestarter

A new de-ion combination linestarter, consisting of a magnetically operated linestarter and a manually operated motor circuit switch combined in the same streamlined cabinet, is announced by the Westinghouse Electric & Manufacturing Company. It is especially designed for across-the-line starting of squirrel cage motors, or as primary switch for wound-rotor induction motors.





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Alsimag insulators made by American Lava Corporation are custom made within the full meaning of this expression.

You can select from a wide variety of materials exactly suited to the requirements of your specific application. We can give you materials which have such outstanding properties as low dielectric loss at ultra high frequencies and at elevated temperatures, low coefficient of thermal expansion, high dielectric constant, machinability after firing, and others too numerous to mention here.

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Outstanding new feature of the linestarter is the safe-locking design of handle and cabinet. With the insertion of one padlock the unit can be locked in off position and the door locked shut. Heretofore all starters have required two padlocks to provide this safety. To make it more safe, the door cannot be opened with the switch in "on" position.

The starter has fuseless circuit protection, by an instantaneous magnetic trip circuit breaker. There are no elements to renew after circuit tripping. Breaker is reset by moving external handle. The breaker handle is a positive indicator, showing whether breaker is "on," "off," or "tripped."

Additional information may be obtained from department 7-N-20, Westinghouse Electric & Manufacturing Company, East Pittsburgh, Pennsylvania.

Bacteria-Killing "Sterilamp" Applied to Household Refrigerators

The recently developed "Sterilamp" for sterilizing the food compartment with ultraviolet rays is announced as a "plug-in" accessory for 1939 refrigerators, manufactured by Westinghouse Electric and Manufacturing Company, Mansfield, Ohio. The "Sterilamp" is a six-and-a-half-inch mercury vapor lamp enclosed in a tube of special glass, which permits the emission of ultraviolet to which ordinary glass is opaque. It uses less than one-fourth as much current as an ordinary 25-watt household lamp, operates continuously on less than two and one-half kilowatt hours a month, and gives off no appreciable heat; yet its radiation is able to kill bacteria and micro-organisms.

During experiments in the company's research laboratories, the Westinghouse "Sterilamp" demonstrated its ability to sterilize very thoroughly all culture plates contaminated by contact with the air outside a refrigerator cabinet, provided the plates were not shaded from the lamp's invisible bactericidal rays. Bacteriologists state that almost any kind of mold may grow in household refrigerators. Not only are most kinds of mold very hard to kill but they will grow even at low temperatures. However, they can be controlled by the "Sterilamp." The commonest types are "penicillium" or white mold, and "aspergillus," the technical name for black or green mold.

Small Flexarc A.C. Welders

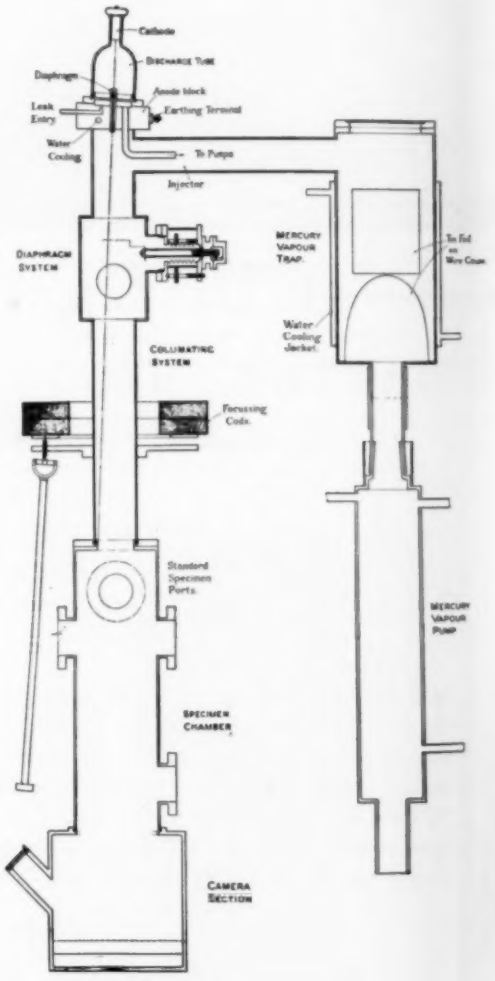
The Westinghouse Electric & Manufacturing Company announces a midget flexarc a.c. welder comprising a special transformer and control for arc welding. It may be used for welding metal furniture frames and light structural steel fabrications. The following specifications are given: current range, 30–140 amperes; coated-electrode capacity, 1/16 inch to 5/32 inch diameter; current adjustment, 12 steps; frequency, 60 cycles; secondary open-circuit voltage, 50 volts on low range, 55 volts on high range; over-all height, 14¼ inches; over-all length, 17⅞ inches; over-all depth, 10¾ inches; weight, 112 pounds.

Insulation by Thin Films

Molecular films only a millionth of an inch thick have been found by the General Electric Company to have insulation values comparable to those of the best known dielectrics. By using areas of film about the size of the head of a pin, the insulation values of various organic materials, such as barium stearate, have been determined. It is necessary to work with such small areas since the capacitance for unit area of such films is very high, and it is necessary to use a small area to keep within the capacitance range of the measuring equipment. A "mercury-drop" electrode is used to insure good contact on these small areas.

Electron Diffraction Camera

The W. Edwards and Company, Vaughan Road, Loughboro' Junction, London, S. E. 5, England, announces a Finch electron diffraction camera. The parts of this camera are shown on the accompanying diagram. Details and prices may be obtained by writing directly to the company.



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